SELF COMPACTING CONCRETE UTILIZING LOCAL MATERIALS

BY

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THESIS ABSTRACT

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SCC is a flowing or continually deforming concrete which consolidates under its own weight, completely filling the formwork, even in the presence of reinforcement without the need for vibrators to form a product free of honeycombs and bug holes. Since its development in 1988, SCC has been used in different countries for various types of concrete structures. However, its use has been limited in Saudi Arabia due to the lack of research data in the region and also the increased cost due to high cement content and use of imported fillers, such as silica fume and fly ash.

The objective of this study was to explore the feasibility of using SCC made with local materials such as natural pozzolan (NP) and limestone powder (LSP).

Twenty trial mixtures were prepared with different proportions of NP and LSP. From these 20 trial mixtures, 15 meeting the flow criteria were selected for further analysis. Five of these mixtures contained 10 to 30% NP; eight of them contained LSP varying between 10 to 40%, first as a replacement of coarse aggregate and second as a replacement of cement. Two ternary mixtures, NP10/LSP10 and NP20/LSP10 and a control mixture containing fly ash FA20/LSP10 was also prepared.

The compressive strength of LSP SCC specimens replacing aggregates was better than that of NP SCC. The SCC with LSP replacing cement recorded the least strength. In terms of the drying shrinkage, sulfate resistance, resistance to corrosion and chloride permeability, the NP SCC specimens proved to be the best with 20% replacement as the optimum, followed by those prepared with LSP. The ternary mixture, NP10/LSP10 also performed excellently in both mechanical and durability properties. Considerable savings could be accrued by the use of these locally available materials. As such, it is recommended to use NP (10 to 30%), LSP (10 to 20%), LSPC (10 to 20%) or NP10/LSP10 in Saudi Arabia, where strength and durability is paramount. Consequently this will lead to a reduction in the consumption of cement and resulting greenhouse gases.

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THESIS ABSTRACT (ARABIC)

ملخص الرسالة

الاســـــــــــم: سلامي ، باباتوندي أبيودون

عنوان الرسالة: الخرسانة ذاتية ألدمك باستخدام مواد محلية

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الخرسـانةالذاتيـة ألـدمك (SCC) تتـدفق ملموسـة أوتتشـكل بشـكل مسـتمر تحـت وزنهـا، وتملـئ تمامـا القوالـب، وحتـى فـي وجـود حديـد التسـليحمـن دون الحاجـة إلـى الهـزاز لتشـكيل المنـتج خاليـا مـن honeycombs والفراغـات منـذ تطـويره عـام 1988 م، الخرسـانة الذاتيـة ألـدمك SCCقـد اسـتخدمت فـي بلـدان مختلفةلأنـواع مختلفـة مـن الهياكـل الخرسـانية. ومـع ذلـك ، فقـد اقتصـر اسـتخدامه فـي المملكـة العربيـة السـعودية نظـرا لعـدم وجـود بيانـات بحثيـةفـي المنطقـة، وكـذلك زيـادة التكـاليف بسـبب ارتفـاع محتـوى الاسمنت واستخدام الحشو المستوردة ، مثل السيليكا فيوم والرماد المتطاير.

وكـان الهـدفمـن هـذه الدراسـة هـو استكشـاف جـدوى اسـتخدام الخرسـانة الذاتيـة ألـدمك SCC مصـنوعة مـن مواد محلية مثل البوزلان الطبيعي (NP) و مسحوق الحجر الجيري (LSP).

عشـرون خلـيطتجريبـي تـم عملهـم مـع نسـب مختلفـة مـنالبـوزلان الطبيعـي (NP)و مسـحوق الحجـر الجيـري (LSP). مـن العشـرون الخلـيط التجريبـي، 15 خلـيط تجربـي تشـابهات مـعمعـاييرَ التـدفقَ وختيـرت للتحليـلِ . خمسـةمـن هـذا الخلـيط احتـوت علـى10 إلـى 30 % (NP)؛ ثمانيـة مـنهماحتـوت علـى (LSP) تَفَـاوُت مـا بـين10؟ إلـى 40 %، أولاً كبـديل للحصـى الخشـن والثانيـة كبـديللإسـمنت. اثنـان مـن الخلطـاتِ الثلاثـي، NP10/LSP10 و NP20/LSP1أضـافه أيضـا إلـى إعـداد خلـيط الـتحكم المحتـوي علـى الرمـاد المتطاير FA20/LSP10.

كانت قوة الضغط للعينات LSP SCC والتي استبدالالحصى فيهاأفضل من NP SCC. كما سجلت SCC مع LSP والتي استبدال الاسمنت فيهاأقل قوة. من ناحية الانكماش الجاف ، ومقاومة الكبريتات، والمقاومة للتآكل والنفاذية للكلوريد، أثبتت عينات NP SCC الأفضل مع استبدال 20 ٪ مثلى، تليها تلك التي أعدت مع LSP. الخليط الثلاثي، NP10/LSP10 يعتبر ممتاز على حد سواء في الخصائص الميكانيكية والمتانة. ويمكن تحقيق وفورات كبيرة عن طريق استخدام هذه المواد المتوفرة محليا. على هذا النحو ، فمن المستحسن استخدام NP (10 إلى 30 ٪) ، LSP (10 إلى 20 ٪) ، LSPC (10 إلى 20 ٪) أو NP10/LSP10 في المملكة العربية السعودية، حيث القوة والمتانة هو الهدف الاساسي. وبالتالي فإن هذا يؤدي إلى انخفاض في استهلاك الاسمنت والغازات المسببة للاحتباس الحراري الناجمة.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF SELF COMPACTING CONCRETE

Self-compacting concrete (SCC) is one of the most widely used concrete types and its development is considered the most sought development in construction industry due to its numerous inherited benefits.

SCC is a flowing or continually deforming concrete which consolidates under its own weight, completely filling the formwork, even in the presence of reinforcement without the use of vibrators to form a product free of honeycombs (i.e., no unfilled spaces within the formwork) and bug holes (i.e., no entrapped air voids). SCC owe this ability to its unique fresh properties and in hardened state, it equals or excels conventionally consolidated concrete with respect to strength and durability. SCC can also be used in situations where it is difficult or impossible to use mechanical consolidation for fresh concrete, such as underwater concreting, cast in-situ pile foundations, machine bases and columns or walls with congested reinforcement. The high flowability of SCC makes it possible to fill the formwork without vibration [1].

SCC was developed first in Japan in the late 1980s to be mainly used for highly congested reinforced structures in seismic regions [2]. As the durability of concrete structures became an important issue in Japan, an adequate consolidation by skilled labors was required to obtain durable concrete structures. This requirement led to the development of SCC and its development was first reported in 1989 [3].

One of the most outstanding advances in the concrete technology remains the development of SCC. Its demand and use has grown significantly in recent years, thanks to its many advantages and financial savings. Presently, it is primarily being applied in the precast industry. The applications of SCC are enormous, limited only by the petite awareness of it in the industry, ability to produce it and acceptance.

SCC consists fundamentally of the same composition as a conventionally vibrated concrete. However, there is a clear difference in their concrete compositions. SCC requires higher proportions of ultra-fine materials and the incorporation of chemical admixtures, particularly an effective super-plasticizer and stabilizer. Ordinary and approved filler materials may include: fly ash, limestone powder, blast furnace slag, and silica fume or quartzite powder.

The method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars [4]. Homogeneity of SCC is its ability to remain unsegregated during transport and placing. High flowability and high segregation resistance of SCC are obtained by:

1. A larger quantity of fine particles, i.e., a limited coarse aggregate content,
2. A low water/powder ratio, (powder is defined as cement plus the fillers such as fly ash, silica fume etc.), and
3. The use of superplasticizer [4].

Because of the addition of a high quantity of fine particles, the internal material structure of SCC shows some resemblance with high performance concrete having self-compactibility in fresh stage, no initial defects in early stage and protection against external factors after

hardening. Due to the lower content of coarse aggregate, however, there is some concern that: (1) SCC may have a lower modulus of elasticity, which may affect the deformation characteristics of prestressed concrete members and (2) creep and shrinkage will be higher, affecting prestress loss and long-term deflection [5].

Three basic characteristics that are required to obtain SCC are: high deformability, restrained flowability and a high resistance to segregation [1]. High deformability is related to the capacity of the concrete to deform and spread freely in order to fill all the spaces in the formwork. It is usually a function of the form, size, and quantity of the aggregates, and the friction between the solid particles, which can be reduced by adding a high range water-reducing (HRWR) admixture. Restrained flowability represents how easily the concrete can flow around obstacles, such as reinforcement, and is related to the member geometry and the shape of the formwork. Segregation is usually related to the cohesiveness of the fresh concrete, which can be enhanced by adding a viscosity-modifying admixture (VMA) along with a HRWR, by reducing the free-water content, by increasing the volume of paste, or by some combination of these constituents. Two general types of SCC can be obtained: (1) one with a small reduction in the coarse aggregates, containing a VMA, and (2) one with a significant reduction in the coarse aggregates without any VMA.

The use of SCC offers many advantages to the construction practice, such as the elimination of consolidation that results in reducing the efforts of and cost of placement, shortening of the construction time and therefore improving the productivity. The use of SCC also leads to a reduction in the noise during casting, better working conditions and the possibility of expanding the placing times in inner city areas. The benefits of SCC also include the homogeneity of concrete production and the excellent surface quality without blowholes and other surface defects. Since its inception, it has been widely used in large

construction in Japan [4]. Recently, this concrete has gained wide use in many countries for different applications and structural configurations [2].

While SCC has been used in other parts of the world, its use in the middle-east, especially Saudi Arabia is still limited. The reluctance, in Saudi Arabia, in utilizing the advantages of SCC stems from two contributing factors: lack of research and published data on the possibility of producing SCC utilizing local materials and doubts in the minds of practising engineers about the reliability of SCC in its hardened stage [6]. The utilization of local materials became an option when the pozzolanic materials are not available locally and if used would increase the cost of concrete production, hence the need to use other fine locally available materials, such as limestone powder, natural pozzolan etc., to reduce the production cost and produce durable concrete.

Since the quantity of cement in SCC is more than that of conventional concrete, it may have some drawbacks, such as autogenous shrinkage. The high heat of hydration that is generated, particularly during the hot weather conditions, may also contribute to internal cracking of SCC which may lead to diffusion of moisture, oxygen, chlorides, sulfates and carbon dioxide from the external environment. This aspect has not been addressed so much in the literature and needs to be thoroughly investigated.

To produce SCC, the major work involves designing an appropriate mix proportion and evaluating the properties of the concrete thus obtained. In practice, SCC in its fresh state shows high fluidity, self-compacting ability and segregation resistance, all of which contribute to reducing the risk of honey combing of concrete [7]. With these good properties, the SCC produced can greatly improve the reliability and durability of the reinforced concrete structures.

1.2 NEED FOR THIS RESEARCH

Self-compacting concrete is no doubt novel in the middle-east region of the world, Saudi Arabia inclusive. Despite having mentioned its merits, local acceptance is still in its early stage. This is due to lack of sufficient information on the use of this new generation concrete, although it has received some publicity in the last seven years. However, research studies have not been so extensive to address pertinent issues as a result of its use, since the technology is still relatively embryonic in the region. Consequently, there is a need for more studies into the behavior of this newly evolving concrete.

The majority of applications thus far have been small niche pours into congested areas, domes, or thin wall sections. In UAE, specifically in Dubai, there are a few high-rise structures under construction using SCC and many more are expected in the near future [8]. Recently, information revealed that SCC was used in construction of the 'Al-Turki Business Park' in which Riyadh road aggregate was used. Also, SCC will be used for the proposed 'Al-Othman Tower' project. This 'green light' shows that the novel concrete is gaining recognition in the Kingdom and its use will become more popular in the future.

However, the awareness in the Kingdom of Saudi Arabia regarding SCC is somewhat muted and this explains the lack of more commercial use of SCC in the Kingdom thus far. The reluctance in utilizing the advantages of SCC, if any, in Saudi Arabia, stems from some of the following contributing factors:

i) The amount of research and published data relating to locally produced SCC is still meager.

ii) The potential problems with local aggregates, such as high porosity, water absorption, softness, excessive dust and low coefficient of thermal expansion when compared with hardened cement mortar in the production of SCC, and

iii) The prevalent harsh environmental conditions in the region. The climate of this region is characterized by high temperature and humidity with their diurnal and seasonal large fluctuations.

Therefore, there is a need to conduct studies on SCC using local aggregates and local filler materials.

1.3 SCOPE AND OBJECTIVES

The scope of this work was the development of suitable mix designs to satisfy the requirements of SCC in the plastic state using local materials and then to determine the strength and durability properties of such concrete.

The general objective of this study was to conduct a comprehensive experimental program on developing an SCC mix utilizing local materials. The specific objectives of this study are the following:

- To develop an optimal mix for SCC utilizing local materials such, as limestone powder and natural pozzolan,
- To evaluate the mechanical properties and durability of the developed SCC,
- To conduct comparative cost analysis between the developed SCC utilizing local materials and conventionally vibrated concrete (CVC), and
- To provide recommended areas of usage of developed SCC utilizing the locally available materials.

1.4 WORKPLAN

The research work was conducted in five phases. A general overview of the phases involved is shown in Figure 1.1. The first phase included a comprehensive literature survey and data collection in the following areas:

1. Flow behavior of SCC using non-conventional fillers, such as fly ash, silica fume, etc.
2. Characteristics and properties of SCC.
3. Methods of testing SCC.
4. Mix design and durability of SCC.
5. Comparison between mechanical properties of SCC and CVC.
6. Numerical modeling of the influence of some parameters on SCC.

The second phase involved upgrading and calibration of the equipment and molds. The equipment for V-funnel and U-tube tests were fabricated to evaluate the self-compactability of freshly prepared SCC. Molds were fabricated for casting different types of specimens required for assessing the properties of hardened SCC.

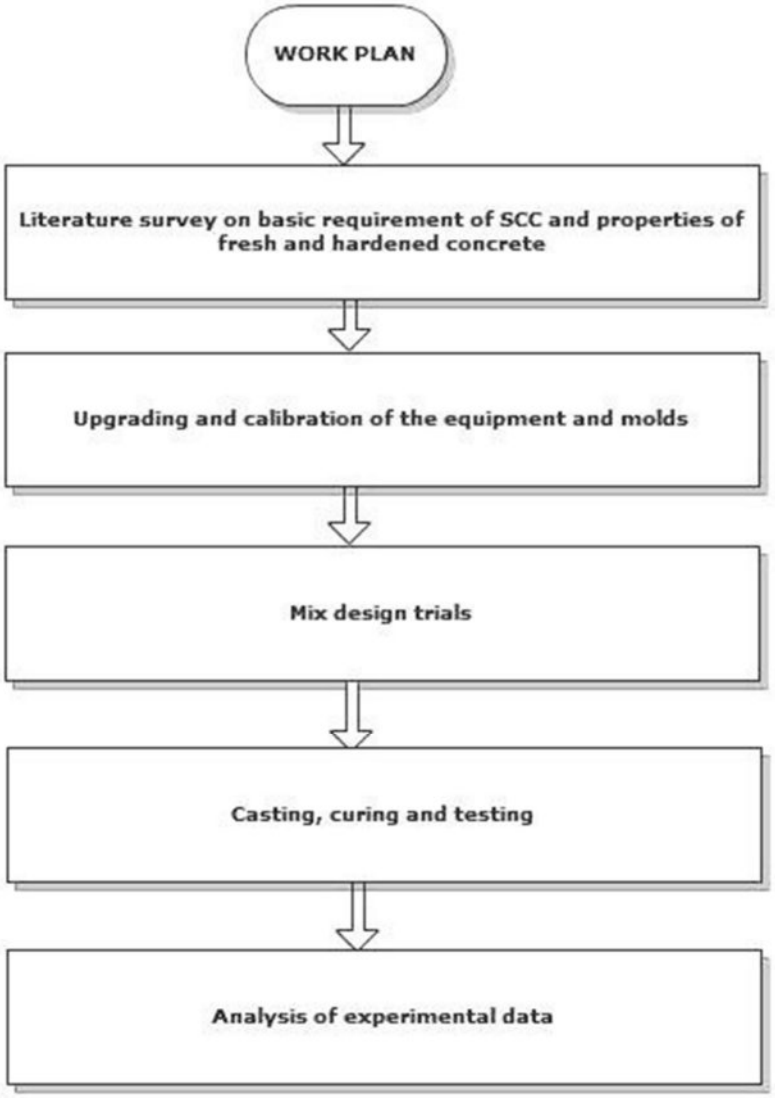


Figure 1. 1: Phases of Research work

In the third phase, the mix design of a suitable SCC was carried out in an investigative fashion. A series of trials were conducted to develop suitable mixtures utilizing local aggregates. Twenty trial mixtures were prepared by varying the quantities of superplasticizer, Glenium-51® and stabilizer, Stream-2® contents. The FA/CA ratio was

constant at 50-50. Out of the trial mixes, suitable mix designs were adopted with self-compactability and flowability as the criteria for selection.

In the fourth phase, different specimens ranging from cubes, big and small cylinders were cast and cured for 3, 7, 14, 28 and 90 days. After 28 days of curing, the smaller cylindrical specimens were exposed to sulfate solution for a period of six months; larger cylindrical specimens were tested for chloride permeability, and the prism for drying shrinkage. The cubic specimens were tested for compressive strength at 3,7,14, 28 and 90 days.

The fifth phase, involved the analysis of the experimental data.

CHAPTER TWO

LITERATURE REVIEW

2.1 DEVELOPMENT OF SELF COMPACTING CONCRETE

For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan. To make durable concrete structures, sufficient compaction by skilled workers was required. However, the gradual reduction in the number of skilled workers in Japan's construction industry led to a similar reduction in the quality of construction work. One solution for the achievement of durable concrete structures independent of the quality of construction work, was the employment of self-compacting concrete, which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating or consolidation.

The history and development of SCC can be divided into two key stages: its initial development in Japan in the late 1980s, when concrete durability, constructability and productivity became a major topic of interest in the country and its subsequent introduction into Europe through Sweden in the mid to late 1990s.

SCC was first developed in Japan in 1988 in order to achieve durable concrete structures by improving the quality in the construction process. It was also found to offer economic, social and environmental benefits over traditional vibrated concrete construction. Okamura [3] proposed the use of SCC in 1986. Studies to develop SCC, including a fundamental study on the workability of concrete, were carried out by Ozawa and Maekawa at the University of Tokyo in 1988, the first practical prototypes of SCC were produced.

After the development of this prototype SCC, intensive research began in many places in Japan, especially within the research institutes of large construction companies, and as a result, SCC was used in many applications. By the early 1990s, Japan started to develop and use SCC and, as of 2000, the volume of SCC used for prefabricated products and ready-mixed concrete in Japan was over 400,000m^3 [9, 10].

In the second half of the 1990s, interest and use of SCC spread from Japan to other countries, including Europe. Sweden was the first country in Europe to begin the development of SCC. Research and development work into SCC in Europe began in Sweden in the 1990s and now nearly all the countries in Europe conduct some form of research and development into the material [10, 11].

In 1996, several European countries formed the "Rational Production and Improved Working Environment through using SCC" project in order to explore the significance of published achievements in SCC and develop applications to take advantage of the potentials of SCC. Since then, SCC has been used successfully in a number of bridges, walls and tunnel linings in Europe [9].

During the last three years, interest in SCC has grown in the United States, particularly within the precast concrete industry. SCC has been used in several commercial projects [9, 11]. Numerous research studies by Khayat et al. [12], Chan et al. [13] and Sonebi et al. [14], have been conducted recently with the objective of developing raw material requirements, mixture proportions, material requirements and characteristics, and test methods necessary to produce and test SCC.

The latest studies related to SCC focused on improved reliability and prediction of properties, production of a dense and uniform surface texture, improved durability, and both high and early strength permitting faster construction and increased productivity [1, 12-15].

2.2 BASIC PRINCIPLES AND REQUIREMENTS OF SCC

SCC is a concrete which gets compacted due to its self-weight and is de-aerated (no entrapped air) almost completely while flowing in the form work. In densely reinforced structural members, it fills completely all the voids and gaps and maintains nearly horizontal concrete level after it is placed. The properties of SCC are achieved by limiting aggregate wherein energy required for flowing is consumed by internal stress (it is increased due to the decreased distance between particles that is due to high deformability) resulting in blockage of aggregate particles. Limiting coarse aggregate content whose energy consumption is intense to a level lower than normal is effective in avoiding this type of blockage. The high flowability with high deformability can be achieved only by the use of a super-plasticizer keeping the w/c ratio to a very low value [16]. Figure 2.1 explains the process of developing compactability of SCC.

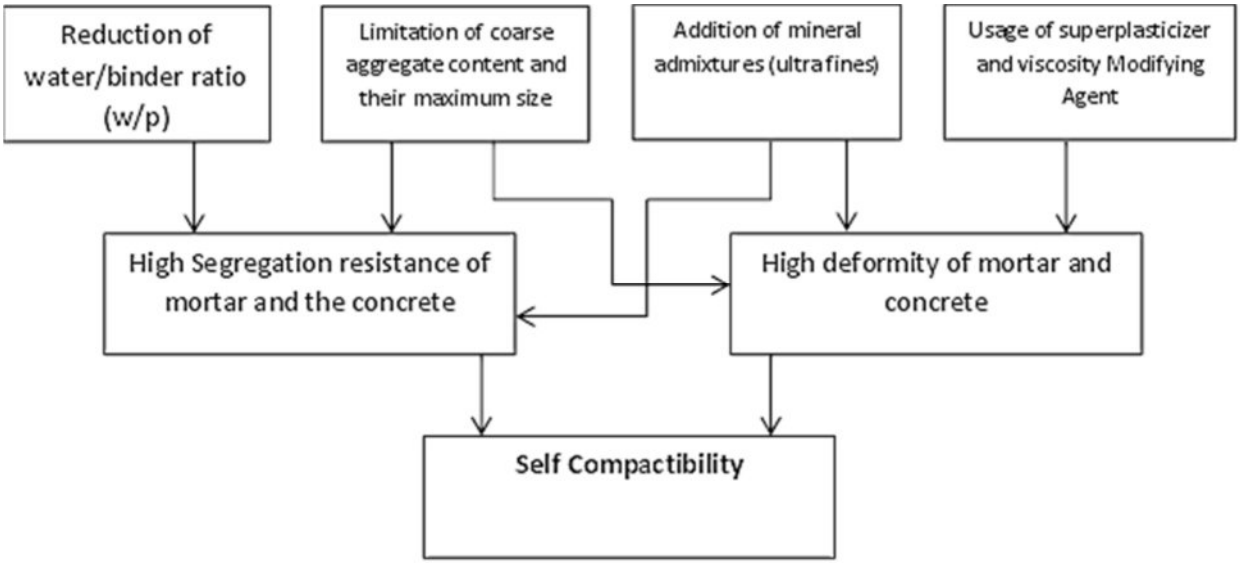


Figure 2. 1: Basic principles for the production of SCC [16].

The reasons for better performance of SCC are attributed to better microstructure and homogeneity. Many investigations, carried out by means of efficient microscopes/SEM etc., have shown an improved microstructure of SCC compared to CVC. The void ratio of SCC in the interfacial transition zone between cement paste and aggregate has been found to be lower and the pores have been distributed much more evenly [3].

With regard to its composition, SCC consists of the same components as CVC, which are cement, aggregates, water, additives and admixtures. However, high volume of superplasticizer for the reduction of the liquid limit and for better workability, the high powder content as "lubricant" for the coarse aggregates, as well as the use of viscosity-agents to increase the viscosity of the concrete have to be taken into account [16].

Okamura and Ozawa [17] have employed the following methods to achieve self-compactability of SCC:

1. Limited aggregate content (coarse aggregate 50% of the concrete volume and sand 40% of the mortar volume),
2. Low water/powder ratio, and
3. Use of higher dosage of superplasticizer.

A concrete mix can only be classified as SCC if the requirements for all the following three workability properties are fulfilled [18]:

1. Filling ability,

2. Passing ability, and

3. Segregation resistance.

Filling ability: It is the ability of SCC to flow into all spaces within the formwork under its own weight. Tests, such as slump flow, V-funnel etc, are used to determine the filling ability of fresh concrete.

Passing ability: It is the ability of SCC to flow through tight openings, such as spaces between steel reinforcing bars, under its own weight. Passing ability can be determined by using U-box, L-box, Fill-box, and J-ring test methods.

Segregation resistance: The SCC must meet the filling ability and passing ability with uniform composition throughout the process of transport and placing.

A wide range of test methods has been developed to measure and assess the compactibility of SCC [18, 19]. Table 2.1 lists the most common tests grouped according to the property assessed.

Table 2. 1: Test Methods for evaluating the compactibility of SCC [19].

Property	**Test method**	**Measured value**
Flowability/filling ability	Slump-flow	Total spread
	Kajima box	Visual filling
Viscosity/flowability	T_{500}	Flow time
	V-funnel	Flow time
	O-funnel	Flow time
	Orimet	Flow time
Passing ability	L-box	Passing ratio
	U-box	Height difference
	J-ring	Step height, total flow
	Kajima box	Visual passing ability
Segregation resistance	Penetration	Depth
	Sieve segregation	Percent laitance
	Settlement column	Segregation ratio

No single test is capable of assessing all of the key parameters of SCC. A combination of tests is required to fully characterize the flowability of an SCC mix.

A simple apparatus and a rapid method for testing the segregation resistance of SCC have been recently developed [20]. The developed apparatus and method are useful in rapidly assessing the segregation resistance of SCC in both vertical and horizontal directions. The proposed method can also distinguish between different CA/TA ratios, different water/binder ratios, and different materials. The selfcompactibility tests commonly conducted on SCC mixes are briefly described in the following subsections.

2.2.1 Slump Flow Test

The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. The test method is based on the conventional slump test. The diameter of

the concrete circle is a measure for the filling ability of the concrete. It is the most commonly used test, and gives a good assessment of filling ability. It gives no indication of the ability of the concrete to pass between reinforcement without blocking, but may give some indication of resistance to segregation. The higher the slump flow value, the greater is its ability to fill formwork under its own weight. Acceptable range for SCC is from 650 to 800 mm [18].

2.2.2 V-funnel test

This test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate size of 20 mm. The funnel is filled with about 12 liters of concrete and the time taken for it to flow through the apparatus is measured. The test measures the ease of flow of the concrete; shorter flow times indicate greater flowability. For SCC, a flow time in the range of 6 to 12 seconds is considered appropriate [18]. The inverted cone shape restricts the flow, and prolonged flow times may give some indication of the susceptibility of the mix to blocking.

2.2.3 U-box test

This test is used to measure the filling ability of SCC. The apparatus consists of a vessel that is divided by a middle wall into two compartments. It provides a good direct assessment of filling ability. For conducting the U-box test, one of the compartments of the apparatus is filled with the concrete and it is allowed to stand for 1 minute. Then the sliding gate is lifted to allow the concrete to flow out into the other compartment. After the concrete comes to rest, the height of the concrete in the compartment that has been filled is measured in two places and the mean height (H1) is calculated. Also, the height in the other compartment (H2) is measured. The filling height is then calculated as H1- H2. The whole test has to be performed within 5 minutes. If the concrete flows as freely as water, at rest it

will be horizontal, so H1- H2 = 0. Therefore, the nearer this test value, i.e., the 'filling height', is zero, the better the flow and passing ability of SCC [18].

Typical acceptance criteria for SCC with a maximum aggregate size of up to 20 mm are presented in Table 2.2.

Table 2. 2: Acceptance criteria for SCC [18].

Method	**Unit**	**Typical range of values**	
		Minimum	**Maximum**
1. Slump flow by Abram's cone	mm	650	800
2. $T_{50\ cm}$ slump flow	sec	2	5
3. J-ring	mm	0	10
4. V-funnel	sec	6	12
5. Time increase, V-funnel at $T_{5\ min}$	sec	0	+3
6. L-box (h_2/h_1)	ratio	0.8	1.0
7. U-box (h_2-h_1)	mm	0	30
8. Fill-box	%	90	100
9. GTM screen stability test	%	0	15
10. Orimet	sec	0	5

In order to obtain adequate deformability, it is important to minimize the friction between the solid particles of the mixture. The reduction of the coarse aggregates and an increase in the paste volume is required to achieve the desired deformability [1].

In order to ensure that the SCC has not lost its uniformity during transport and placing due to its highly flowable and self-leveling nature, it is suggested that the in-situ tests, such as rebound hammer, pull-out, etc. should be conducted. Non-variations in these near-surface properties may be considered as an indication of no loss of uniformity [21].

The size and quantity of coarse aggregates in a SCC mixture are directly related to the concrete passing ability. The passing ability requirements depend on the formwork geometry and the extent of congestion of the reinforcement. The risk of blockage is reduced by providing adequate viscosity.

Adequate cohesiveness can be obtained by incorporating a viscosity-modifying admixture (VMA) along with a high range water reducing admixture to control bleeding, segregation, and surface settlement [22].

2.3 BASIC MATERIALS OF SCC

The integral materials used for the production of SCC are not different from those used for CVC, except that SCC contains lesser aggregate and greater powder (cement and filler particles smaller than 0.125 mm) content. Fly ash, glass filler, limestone powder, silica fume, natural pozzolan, etc., are used as the filler materials. To improve the selfcompactibility, without segregation, a superplasticizer along with a stabilizer is added.

2.3.1 Powder (Mixture of Portland cement and Filler)

The term 'powder' used in SCC refers to a blended mix of cement and filler particles smaller than 0.125 mm. The filler increases the paste volume required to achieve the desirable workability of SCC. The addition of filler in an appropriate quantity enhances both workability and durability without sacrificing early strength [5].

Cement

Cement used for SCC should not contain C_3A content more than 10% to avoid the problems of poor workability retention [18]. The selection of the type of cement depends on the overall requirements for concrete, such as strength and durability.

Filler

Materials, such as fly ash, blast furnace slag, ground glass, limestone powder, silica fume, natural pozzolan, etc., are commonly used as filler for producing SCC. Savings in labor costs might offset the increased cost related to the use of more cement and superplasticizer, but the use of limestone powder (LSP) as a filler could increase the fluidity of the concrete, without any increase in the cost [23]. Since the natural pozzolan is used in the present investigation, a detailed description of this material is provided in the following paragraphs.

Natural Pozzolan: ASTM C125 defines pozzolan as "a siliceous and aluminous material which in itself possesses little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties". Pozzolan can be added to cement during the production or mixed directly into concrete.

It is well known that the incorporation of pozzolans into cement or concrete systems provides benefits to properties of both fresh and hardened concrete, such as improvement in workability, reduction in the heat of hydration, decreased permeability, increased ultimate strength and reduction in alkali-silica expansion [24].

The use of a natural pozzolan has been found to improve the fresh and hardened properties of SCC [25].

The use of pozzolanic materials in the construction industry has been a common practice for many years. The use of supplementary materials, like natural pozzolans has improved the durability of concrete [26], enhanced impermeability and chemical durability, improved resistance to thermal cracking and increase in ultimate strength [27]. Natural pozzolans have been widely used as substitutes for Portland cement in many applications because of their advantageous properties which include cost reduction and CO_2 emission reduction, decreased permeability and increased chemical resistance [28]. However, most pozzolanic materials, especially natural pozzolans, tend to increase the mixing water requirement for concrete and lower the rate of strength development [24].

The use of natural pozzolan is widespread in Europe and Asia than in the United States because of its availability in those parts of the world. The four largest producers of natural pozzolans are Italy, Chile, Greece and Cameroon as shown in Table 2.3.

Table 2. 3: World production of natural pozzolan in 2003 [29]

Country	Commodity	Production, kt
Algeria	Pozzolan	400
Austria	Trass	5
Cameroon	Pozzolan	600
Cape Verde	Pozzolan	1
Chile	Pumice and Pozzolan	830
Ecuador	Pozzolan	23
France	Pozzolan and Lapilli	450
Greece	Pozzolan	750
Honduras	Pozzolan	190
Italy	Pozzolan	4000
Saudi Arabia	Pozzolan	160
Tanzania	Pozzolanic materials	43.3
Uganda	Pozzolanic materials	12.4
Total pozzolan production*		6,180.00

In the Kingdom of Saudi Arabia, the natural pozzolanic material is available from basalt plateaus (harrat) spread within the "Edge of Arabian Shield". The area of these plateaus is about 90000 km^2 in the east of the escarpment onwards to the coast of the Red Sea. Out of this area Harrat al Hutaymah, Harrat Lunayyir, midwest Harrat Rahat, Harrat Al Birk and Harrat Khaybar contains pozzolanic material which can be used for manufacture of concrete [30, 31].

Since natural pozzolans are available in Saudi Arabia, the exploitation of pozzolanic or both pozzolanic and cementitious properties of mineral admixtures, when used as a partial replacement of cement, can lead to a considerable economic benefit and durability.

The durability of concrete using natural pozzolan was captured in the atlas of industrial minerals [30], whose principal finding was the substantial sulfate resistance that was achieved by using Portland pozzolan cement with clinker Type I or V. Its significance is that it increases the sulfate resistance when it is added as a mineral admixture. The amount of natural pozzolan used did not exceed 30% of cement weight.

Turanli and Uzal [24] examined the characteristics of laboratory produced blended Portland cement concrete using natural pozzolan in the tune of 55% by weight of cement with w/c ratio of 0.45 and its effect on the properties of concrete produced was studied. The compressive strength of the blended cements concrete at ages up of to 28 days was lower than that of reference Portland cement concrete but at 91 days, the results were similar. It also reduced the alkali-silica expansion.

Limestone Powder: Limestone means any rock formed mostly of calcium carbonate ($CaCO_3$), but to geologists, limestone is only one of several types of "carbonate rocks."

These rocks are composed of more than 50% carbonate minerals, generally the minerals calcite (pure $CaCO_3$) or dolomite (calcium-magnesium carbonate, $CaMg(CO_3)_2$) or both.

In general, LSP is referred to as materials with particle sizes less than 0.125 mm [32] and these include cementitious and inert fillers. Billberg [33] opined that the rheology of concrete can only be optimized if the fine mortar part of concrete is designed so that its rheology is optimized. In this respect, fine mortar phase refers to particles less than 0.25 mm. Inert fillers such as limestone are traditionally used to increase the powder content of SCC mixes. More recently, mineral admixtures have also been considered [33, 34].

Zhu et al. [35] investigated different limestone and chalk powders in SCC, the results indicated that all the different limestone and chalk powders selected could be used successfully for producing SCC mixes, but with modest adjustments of superplasticizer dosage. Generally, higher superplasticizer dosages were required for SCC using chalk powder than for that using limestone powder. The fineness of the powders had little effect on the superplasticizer demand. The results also indicated that the compressive strength of the SCC mixes containing limestone and chalk powders was significantly greater than that of conventional concrete at the same water /cement ratio, particularly at early ages [35].

Bosiljkov [36] investigated the influence of finely ground limestone and crushed limestone dust on the properties of SCC mixes in the fresh and hardened state. The results indicated that finer and better-graded limestone significantly increased the deformability of the paste. When a high volume of this filler was added to the SCC mix, the required SCC was achieved at a lower water to powder ratio and the 28–day compressive strength of concrete mixes improved [36].

Naik et al. [37] studied the possibility of using limestone-quarry by-product material and class C fly ash in the development of economical SCC. Based on the extensive laboratory work, it was concluded that the limestone-quarry fines and class C fly ash have high potential for utilization in the preparation of SCC. The test data indicated that these materials can be used in the manufacturing economical SCC in several different ways. When quarry fine material was used as a substitute of natural sand, it reduced the requirement of chemical admixtures, high-range water-reducing admixtures and viscosity-modifying admixture without affecting the strength of SCC. The 28-day compressive strength of the mixtures made with sand replaced with quarry fines was in the range of 7,500 psi and 9,000 psi, qualifying the mixtures to be classified as high-strength SCC (≥6,500 psi). Also, by using class C fly ash for the replacement of up to 55% of total cement by mass, high-strength SCC with 28-day strength in the range of 9,000 psi to 10,000 psi was produced in an economical way. The conclusion was that the use of quarry fines and class C fly ash significantly reduced the amount of expensive chemical admixtures in producing SCC [37].

Ho et al. [38] investigated the utilization of alternative materials, such as quarry dust, for SCC applications. Results from rheological measurements on pastes and concrete mixes incorporating limestone or quarry dust were compared. It was found that the quarry dust, as supplied, could be used successfully in the production of SCC. However, due to its shape and particle size distribution, mixes with quarry dust required a higher dosage of superplasticizer to achieve similar flow properties [39].

2.3.2 Aggregate

The maximum size and grading of the aggregates depends on the particular application. Maximum size of aggregate in SCC is usually limited to 20 mm. The coarse

aggregate content in SCC is kept either equal to or less than that of the fine aggregate content.

Bui et al. [20] proposed a rheological model for SCC relating the rheology of the paste to the average aggregate spacing and average aggregate diameter to consider the effect of most of the factors related to aggregate properties and content.

According to Bui et al. [20] and other researchers, a higher aggregate spacing requires a lower flow and higher viscosity of the paste to achieve satisfactory deformability and segregation resistance of SCC. Better results were also obtained with the same spacing and a smaller aggregate diameter. For SCC mixtures, a coarse aggregate size of 5 mm to 14 mm and quantities varying from 790 kg/m^3 to 860 kg/m^3 have been used with satisfactory results [1].

The sand ratio (i.e., fine aggregate volume/total aggregate volume) is an important parameter for SCC and the rheological properties improved with an increase in the sand ratio [40].

According to Okamura [17], if the coarse aggregate content in a SCC mixture exceeds a certain limit, blockage would occur independently of the viscosity of the mortar. Superplasticizer and water content are then determined to ensure desired self-compacting characteristics. Mata [5] reported that reducing the volume of coarse aggregates in a SCC mixture is more effective than decreasing the sand-to-paste ratio to increase the passing ability through congested reinforcement.

The aggregate packing factor (i.e., the ratio of mass of aggregates of tightly packed state in SCC to that of loosely packed state in air) determines the aggregate content, and influences the strength, flowability and self-compacting ability [7].

The coarse aggregate should not contain clay seams that may produce excessive creep and shrinkage. Therefore, aggregates must be clean for incorporation in the mix [41].

The moisture content of aggregates should be closely monitored and must be taken into account in order to produce SCC of constant quality [18].

2.3.3 Admixtures

Superplasticizers: Superplasticizer (SP) is an essential component of SCC to provide the necessary workability. The superplasticizer to be selected should have: (i) high dispersing effect for low water/powder ratio (less than 1 by volume), (ii) maintenance of the dispersing effect for at least two hours after mixing, and (iii) less sensitivity to temperature changes [4, 42].

The main purpose of using a super plasticizer is to produce flowing concrete with very high slump that is to be used in heavily reinforced structures and in places where adequate consolidation by vibration cannot be readily achieved. The other major application is the production of high-strength concrete at w/c's ranging from 0.3 to 0.4. The ability of a superplasticizer to increase the slump of concrete depends on such factors as the type, dosage, and time of addition, w/c and the nature or amount of cement. It has been found that for most types of cement, a superplasticizer improves the workability of concrete.

Some of the benefits/features of a super plasticizer are:

1. Specified strength can be achieved at high workability,
2. Faster placement with reduced labor and equipment costs, and
3. Low permeable concrete leading to enhanced durability.

Some of the benefits of a high-range water reducer are:

1. Higher strength can be achieved at "normal" workability without the need for additional cement,
2. The reduction in the water content typically reduces bleeding,
3. Produces cohesive and workable concrete at high slump, and
4. Reduction in striking times.

Some of the applications of a superplasticizer are:

1. Incorporating the admixture during batching or on delivery at site increases workability to a flowing or self-leveling state,
2. Heavily reinforced sections,
3. Deep sections where normal consolidation is difficult,
4. High quality formwork finishes,
5. Pumped concrete (long pipelines), and
6. Compatible with all types of Portland cements, including sulfate-resisting cements and blends.

Stabilizer: Other types of admixtures may be incorporated as necessary, such as VMA for stability, air-entraining admixture (AEA) to improve freeze-thaw resistance, retarders for control of setting, etc.

Lachemi et al. [43] have carried out a study on the performance of new VMAs in enhancing the rheological properties and consistency of SCC. They found that the combined use of proper dosages of VMA and SP contribute to securing high-performance cement pastes that is highly fluid yet cohesive enough to reduce water dilution and enhance water retention.

2.3.4 Ranges of the quantities of the Constituent Materials for SCC

Typical ranges of proportions and quantities of the constituent materials for producing SCC are given below:

1. Water content: 170 to 176 kg/m^3 [7]. It should not exceed 200 kg/m^3 [18].
2. Cement content: 350 to 450 kg/m^3 [18],
3. Total powder content (i.e., cement + filler): 400 to 600 kg/m^3 [18],
4. Dosage of superplasticizer: 1.8% of the total powder content (by mass) [7]. However, the recommended dosage varies from product to product.
5. Water/powder ratio: 0.80 to 1.10 (by volume) [18]. A water/powder ratio in the range of 0.30 to 0.38 (by mass) for tropical Middle East conditions [8, 44].
6. Coarse aggregate content: 28 to 35% by volume of the mix, i.e., 700 to 900 kg/m^3 of concrete [18].
7. The sand content balances the volume of other constituents. The sand content should be greater than 50% of the total aggregate content [8, 44]. Sand ratio (i.e. volume ratio of fine aggregate to total aggregate) is an important parameter in SCC and the rheological properties increase with an increase in sand ratio. Sand ratio should be taken in the range of 50 to 57% [7], and
8. The aggregate packing factor: 1.12 to 1.16 [7].

2.4 MIX DESIGN FOR SCC

A flow-chart describing the procedures for design of SCC mix is shown in Figure 2.2 [18].

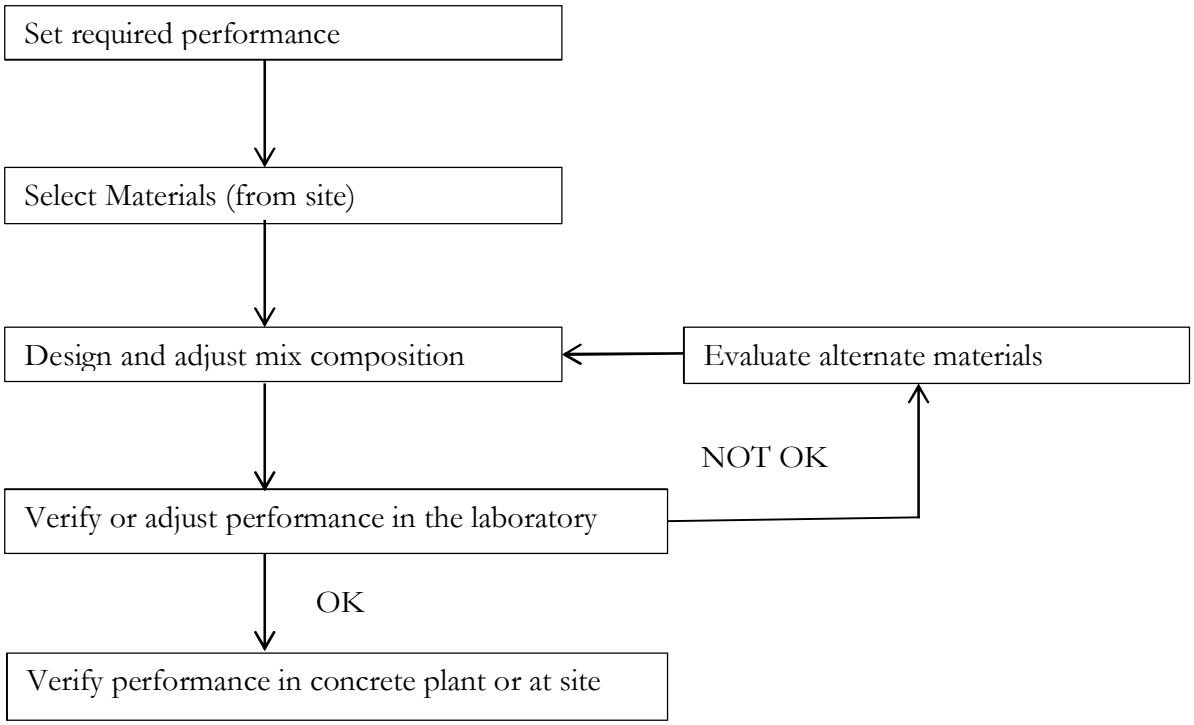


Figure 2. 2: SCC mix design procedure [18].

Okamura and Ozawa [17] have proposed a simple mix proportioning system for SCC. The coarse and fine aggregate contents are fixed so that self-compactibility can be achieved easily by adjusting the water/powder ratio and superplasticizer dosage only.

The mix design procedure is as follows:

1. The coarse aggregate content (all particles larger than 4 mm and smaller than maximum size of aggregate) is fixed in the range of 50 to 60% of the solid volume or 28 to 35% of the concrete volume or 700 to 900 kg per cubic meter of concrete.
2. The fine aggregate content (all particles larger than 0.075 mm and smaller than 4 mm) is fixed in the range of 40 to 50% of the mortar volume.

3. The water/powder ratio is assumed in the range of 0.8 to 1.0 (by volume), depending on the properties of the powder (i.e., cement and filler having particles smaller than 0.125 mm).
4. The superplasticizer dosage and the final water/powder ratio are determined through trial mixes so as to ensure self-compactibility using U-flow, slump-flow and V-funnel tests. Target values are U-flow of 0 to 30 mm, slump-flow of 650 to 800 mm, and V-funnel time of 6 to 12 seconds.

   A simple mix design method for SCC has been proposed by Su et al. [7].

Compared with the method developed by the Japanese Ready-Mixed Concrete Association (JRMCA), this method is simple, easy for implementation and less time consuming, requires a small quantity of binder and saves cost. This method consists of the following steps:

1. Determination of amounts of aggregates required using the other parameters, such as loosely piled densities of fine and coarse aggregates in SSD condition, volume ratio of fine aggregate to total aggregate and packing factor.
2. Determination of the cement content for a target design compressive strength.
3. Determination of the filler content and water content for the selected water/powder ratio and assumed air content, using the total absolute volume equation.
4. Determination of the dosage of superplasticizer based on the calculated total powder content.
5. Adjustment of the calculated water content for aggregate surface moisture or absorption, if any, and for water content in the superplasticizer.
6. Preparation of the trial mixes and carrying out tests for determining the properties of SCC.
7. Adjustment of mix proportions.

Patel et al. [45] and Sonebi [23, 46] have derived statistical models relating the major SCC properties, such as slump flow, compressive strength, chloride permeability, etc, with the SCC mix parameters, such as water/powder ratio, total powder content, fly ash (filler) content, superplasticizer content, etc. These models can be used as economical tools for the optimum design of fly ash based SCC mixtures with desired properties in practical applications.

Nagamoto and Ozawa [47] have proposed mixture proportions of self-compacting high performance concrete.

During the production of SCC, tests on aggregate grading and moisture content should be carried out more frequently than usual, since SCC is more sensitive than normal concrete to variations in the properties of aggregates. Since the quality of freshly mixed concrete may fluctuate at the beginning of production, it is recommended that workability tests should be conducted until consistent and compliant results are obtained. SCC tends to dry faster than CVC because there is little or no bleed water at the surface. Initial curing should therefore be commenced as soon as practicable after placing in order to minimize the risk of shrinkage cracking.

2.5 PROPERTIES OF HARDENED SCC

2.5.1 Compressive, Tensile, and Bond Strength

Xie et al. [48] have reported a compressive strength of up to 80 MPa with a low permeability, good freeze-thaw resistance, and low drying shrinkage [48]. SCC with a compressive strength of around 60 MPa can easily be achieved. The strength could be further improved by using fly ash as a filler [8]. The characteristic compressive and tensile

strengths have been reported to be around 60 MPa and 5 MPa, respectively [49]. Patel et al. [45] reported 28-days compressive strength values ranging from 31 to 52 MPa. According to Nehdi et al. [50] the 91-days compressive strength was in the range of 28 and 47 MPa.

SCC mixes with a high volume of cement – limestone filler paste can develop higher or lower 28-day compressive strength, compared to those of vibrated concrete with the same water/cementitious materials ratio and cement content, but without filler. It appears that the strength characteristics of SCC are related to the fineness and grading of the limestone filler used [36].

According to Kumar et al. [51] SCC containing more than 50% fly ash of the total powder material produced compressive strengths ranging from 20 to 30 MPa at the ages of 3 and 7 days. SCC with water/cementitious material ratios ranging from 0.35 to 0.45, a mass proportion of fine and coarse aggregates of 50:50 with cement replacement of 40%, 50% and 60% by Class F fly ash and cementitious materials content of 400 kg/m^3 being kept constant, obtained good results for compressive strength ranging from 26 to 48 MPa, which shows that an economical SCC could be successfully developed by incorporating high volumes of Class F fly ash [2].

The bond behavior of SCC was found to be better than that of normally vibrated concrete [16]. The higher bond strength was attributed to the superior interlocking of aggregates due to the uniform distribution of aggregates over the full cross section and higher volume of cement-binder matrix [8].

2.5.2 Modulus of Elasticity

The modulus of elasticity of SCC and that of a CVC, produced from the same raw materials, have been found to be almost identical. Although there is a higher paste matrix

share in SCC, the elasticity remains unchanged due to the denser packing of the particles [49].

The modulus of elasticity of concrete increases with an increase in the quantity of aggregate of high rigidity, whereas it decreases with increasing cement paste and porosity. A relatively small modulus of elasticity can be expected, because of the high content of ultra-fines and additives as dominating factors and, accordingly, minor occurrence of coarse and stiff aggregates at SCC [52].

According to Holschemacher [52], the modulus of elasticity of SCC can be up to 20% lower compared with CVC having same compressive strength and made of same aggregates. Leemann and Hoffmann [53] reported an average modulus of elasticity of SCC to be 16% lower than that of CVC for an identical compressive strength.

Results available indicate that the relationships between the static modulus of elasticity (E) and compressive strength (f'c) were similar for SCC and CVC. A relationship in the form of $E = k.f'c$, where k is a constant, has been widely reported, and all values of this constant were close to the one recommended by ACI 318-02 for structural calculations for normal weight traditional CVC [54]. Average 28-days modulus of elasticity of SCC has been reported to be 30 GPa corresponding to average 28-days cube strength of 55.41 MPa [16].

2.5.3 Rapid Chloride Penetrability

Rapid chloride penetrability of concrete is determined using a standard test method for electrical indication of concrete's ability to resist chloride ion penetration, covered by ASTM C 1202. The rapid chloride permeability test evaluates the performance of various cementitious materials based on the accelerated diffusion of chloride ions under the application of an external electric field. The chloride ion penetrability of different SCC mixes,

as reported by Ramsburg et al [25] are as follows: 2,000 to 4,000 coulombs (categorized as "moderate") for mixes with cement, 1,000 to 2,000 coulombs (categorized as "low"); for mixes with slag cement, and 100 to 1,000 coulombs (categorized as "very low"); for mixes with calcined shale cement. Kapoor et al. [8] have reported a rapid chloride permeability value of 620 coulombs for SCC against 1970 coulombs for CVC.

According to Plante and Bilodean [55], the incorporation of supplementary cementing materials in concrete contributes to the reduction in the porosity of the system, which, in turn, results in a reduction in the chloride ion permeability of concrete. Patel et al. [45] reported the rapid chloride permeability in the range of 772 to 1379 Coulombs with percentage of fly ash in the range of 30% to 60%. According to Nehdi et al. [50] the 91 days rapid chloride penetration value was in the range of 400 to 900 Coulombs. Table 2.4 shows guidelines to evaluate the chloride ion permeability based on the charge passed as per ASTM C1202.

Table 2. 4: Relationship between charge passed and chloride permeability [56].

Charge Passed (Coulombs)	**Chloride Ion Penetrability**
More than 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
Less than 100	Severe

2.5.4 Shrinkage and Creep

Shrinkage and creep of the SCC mixtures have not been found to be greater than those of CVC [54, 57]. Ramsburg et al. [25] have reported the shrinkage of SCC as follows: 0.03% for mixes with cement tested at 14 days, 0.03% to 0.04% for mixes with slag cement tested at 28 days, and 0.04 to 0.045% for mixes with calcined shale cement tested at 28 days. Shrinkage and creep of SCC coincided well with the corresponding properties of normal concrete when the strength was held constant [58]. According to Kapoor et al [8], the drying shrinkage of SCC is similar to that of CVC.

The shrinkage and creep rates of SCC have been found to be approximately 30% higher at an identical compressive strength; this is because of the high amount of paste [53]. Since SCC is rich in powder content and poor in the coarse aggregate fraction, addition of fiber will be effective in counteracting drying shrinkage [59]. The 90 days drying shrinkage value as reported by Xie et al [48] was 383 x 10^{-6} mm/mm. They suggested that SCC with UPFA (Ultra Pulverized Fly Ash) has higher mechanical properties, excellent impermeability and freezing resistance, and lower drying shrinkage.

In a study on SCC incorporating high volumes of class F fly ash, conducted by Bouzoubaa [2], 112-days drying shrinkage was found in the range of 493 to 591 × 10^{-6} and 224-days drying shrinkage was in the range of 504 to 595 × 10^{-6} mm/mm [2].

In another study on SCC incorporating high volumes of class F fly ash, conducted by Patel [45], 112-days drying shrinkage was found to be in the range of 330 to 667 × 10^{-6} mm/mm.

2.5.5 Sulfate Resistance

Persson [60] conducted a laboratory study on sulphate resistance of SCC consisting of 40 cylinders of concrete and compared it with CVC. The specimens were exposed to a solution with sodium sulfate, sea or distilled water for a period of 900 days. The results showed larger loss of mass in SCC than that in CVC when exposed to sodium sulfate solution, while no such loss was noted in the case of water exposure (sea or distilled water).

Uysal and Sumer [61] examined the degree of sulphate attack by using visual examination and reduction in compressive strength The test results showed that among the mineral admixtures used, FA and GGBFS significantly increased the workability and compressive strength of SCC mixtures. Replacing 25% of PC with FA resulted in strength of more than 105 MPa at 400 days. Moreover, the presence of mineral admixtures had a beneficial effect on the strength loss due to sodium and magnesium sulphate attack. On the other hand, the best resistance to sodium and magnesium sulphate attacks was obtained from a combination of 40% GGBFS with 60% PC.

2.6 ECONOMICS OF SCC

Savings in labor costs might offset the increased cost related to the use of more cement and superplasticizer, and the mineral admixtures, such as pulverized fuel ash (PFA), ground granulated blast furnace slag (GGBS) or lime stone powder (LSP), could increase the fluidity of the concrete, without any increase in the cost. These supplementary cementing materials also enhance the rheological parameters and reduce the risk of cracking due to the decreased heat of hydration, and therefore, improve the durability [23].

2.7 LITERATURE SUMMARY

A brief literature review on SCC, as presented above, indicates that SCC has several advantages over the traditional vibrated concrete, mainly the ease and precision in placement and lack of vibration. SCC can be produced using the same raw materials and has either similar or better strength and durability properties compared to the CVC. Some information pertaining to the production and performance of SCC is available in literature in the context of UAE. However, little or no published information is available on the study of SCC in the Eastern Saudi Arabia. Among the little published works in the Kingdom on SCC are those of the research institute (RI) of the university and the works of Shamsad et al [62] and Hameed [10] to mention but a few. As mentioned earlier, the aggregate available in this region is of marginal quality. A study on SCC produced utilizing local materials is therefore needed to promote interest in SCC. Also the use of locally available natural pozzolan on a filler and/or cementitious material needs to be investigated.

CHAPTER THREE

DESIGN AND EVALUATION OF SCC MIXTURES

In this chapter, procedure of selecting a suitable SCC mixes for the evaluation of their performance in terms of strength and durability are described. For selecting a suitable mix using local materials, 20 trial mixtures were considered by varying the mix parameters, such as quantity of fillers (LSP and NP) and superplasticizer and fine aggregate/coarse aggregate ratio, while keeping the water/powder ratio constant. Proportioning of the trial mixtures was carried out using the absolute volume method. Each mixture was tested for the flow properties and suitable mixtures were selected based on the acceptable flow criteria.

3.2 CONSTITUENTS FOR SCC TRIAL MIXES

The following materials were utilized in the trial mixes.

3.2.1 Cement

ASTM C 150 Type I Portland cement which is extensively used in Saudi Arabia was used in this study. The specific gravity of cement used was taken as 3.15. Table 3.1 shows the chemical composition of Type I Portland cement.

Table 3. 1: Chemical composition of Type I cement.

Constituent	Wt %
SiO_2	19.92
Al_2O_3	6.54
Fe_2O_3	2.09
CaO	64.7
MgO	1.84
SO_3	2.61
K_2O	0.56
Na_2O	0.28
L.O.I.	0.73
C_3S	55.9
C_2S	19
C_3A	7.5
C_4AF	9.8

3.2.2 Fine Aggregates

Dune sand was used as fine aggregate. The specific gravity and absorption of the fine aggregates are typically 2.65 and 0.4%, respectively. The grading of the fine aggregate is presented in Table 3.2.

Table 3. 2: Grading of fine aggregates.

Sieve #	Percent Passing
4	100
8	100
16	100
30	76
50	10
100	4

3.2.3 Coarse aggregates

The coarse aggregates used in this study were crushed limestone processed from the local quarries in Abu Hadriah. The maximum aggregate size was 19 mm. The grading of coarse aggregates is shown in Table 3.3. The average values of specific gravity and absorption of the coarse aggregates, determined in accordance with ASTM C 127, were 2.6 and 2.4 %, respectively.

Table 3. 3: Grading of coarse aggregates.

Sieve Opening, mm	Percent Passing
19	100
12.5	90
9.5	45
4.75	0

3.2.4 Filler

Locally available pulverized limestone powder and natural pozzolan were used as fillers. The specific gravity of LSP and NP are 1.394 and 3 respectively. Tables 3.4 and 3.5 show the chemical composition of limestone powder and natural pozzolan, respectively.

Table 3. 4: Chemical composition of limestone powder.

Constituent	Wt %
SiO_2	11.79
CaO	45.7
Al_2O_3	2.17
Fe_2O_3	0.68
MgO	1.80
K_2O	0.84
Na_2O	1.72
$Na_2O+(0.658K_2O)$	2.27
Loss on Ignition	35.10
Moisture	0.20

Table 3. 5: Chemical composition of natural pozzolan.

Constituent	Wt %
SiO_2	42.13
Fe_2O_3	12.21
Al_2O_3	15.37
CaO	8.06
MgO	8.50
K_2O	0.84
Na_2O	2.99
$Na_2O+(0.658K_2O)$	3.54
Loss on Ignition	-
Moisture	0.17

3.2.5 Admixtures

Superplasticizer: Superplasticizer by the trade name of "Glenium® 51" from BASF® Chemical Company was used as superplasticizer. The specific gravity of the superplasticizer as given by the supplier is 1.1 at 20°C and the pH level is 6.6 with chloride content of less than 0.1%. It has been primarily developed for applications in the ready-mix and precast concrete industries where the highest durability and performance is required. It is differentiated from other superplasticizers in that it is based on a unique carboxylic ether polymer with long lateral chains. This greatly improves cement dispersion. The level of fluidity is governed chiefly by the dosing of the superplasticizer. However, overdosing may lead to the risk of segregation and blockage.

Stabilizer: A high performance cohesive agent named "Stream 2" from BASF® Chemical Company, specially designed to ensure a good consistency and stability in concrete with very high fluidity, was used as a stabilizer. The specific gravity of stabilizer "Stream 2" as specified by the supplier is 1.01 at 25°C with chloride content of less than 0.2% and a pH level of 6.

3.3 TRIAL MIXTURES

Twenty trial mixtures were prepared with different proportions of fillers, namely limestone powder (LSP) and natural pozzolan (NP). These mixtures were prepared with cementitious materials content of 450 kg/m^3 and effective water to cementitious materials ratio of 0.40. Table 3.6 shows the weights of constituents in each concrete of the mixture.

Table 3. 6: Constituents of the trial mixtures.

Mix #	w/c ratio*	Weights of Constituents, kg/m^3					Admixture, liter/100 kg Cement	
		Cement	Limestone Powder	Natural Pozzolan	Coarse Aggregate	Fine Aggregate	Glenium-51	Stream-2
1	0.40	405	0	45	907.8	907.8	1.5	0.5
2	0.40	382.5	0	67.5	919.1	919.1	1.5	0.5
3	0.40	360	0	90	930.4	930.4	1.5	0.5
4	0.40	337.5	0	112.5	941.7	941.7	1.5	0.5
5	0.40	315	0	135	953.0	953.0	1.5	0.5
6	0.40	270	0	180	975.6	975.6	1.5	0.5
7	0.40	225	0	225	998.2	998.2	1.5	0.5
8	0.40	450	162.99	0	651.95	814.94	1.5	0.5
9	0.40	450	235.15	0	548.68	783.84	1.5	0.5
10	0.40	450	302.01	0	453.01	755.01	1.5	0.5
11	0.40	450	364.12	0	364.12	728.24	1.5	0.5
12	0.40	450	421.98	0	281.32	703.30	1.5	0.5
13	0.40	450	476.00	0	204.00	680.01	1.5	0.5
14	0.40	450	526.57	0	131.64	658.21	1.5	0.5
15	0.40	405	45	0	865.1	865.1	1.5	0.5
16	0.40	360	90	0	841.4	841.4	1.5	0.5
17	0.40	315	135	0	817.8	817.8	1.5	0.5
18	0.40	270	180	0	794.2	794.2	1.5	0.5
19	0.40	405	45	167.15	668.60	835.75	1.5	0.5
20	0.40	360	90	171.31	685.24	856.55	1.5	0.5

*Water to cementitious materials ratio

The concrete mixtures were designed according to the rational mix-design method, and the proportioning of materials was carried out on weight basis. The mixtures were prepared with a cementitious material content of 450 kg/m^3 and effective water to

cementitious materials ratio of 0.4. The coarse aggregate to total aggregate ratio and fine to total aggregate ratio was in the range 0.3 to 0.5. Natural pozzolan was varied in the range of 10% to 50% while limestone powder was varied in the range of 10% to 40%, first as a replacement for aggregate then as a replacement for Type I Portland cement. Glenium–51 (0.8 to 1.5 liters/100 kg of cement) and Stream-2 (0.5 liters/100 kg of cement) were added to the mixtures in order to produce a flowable concrete. Glenium–51 serves as a plasticizer while Stream–2 is a stabilizer. Table 3.5 shows the details of mix constituents, including fillers investigated and the weights of the ingredients in all SCC trial mixtures that were prepared in this study.

3.4 SELF COMPACTIBILITY TESTS ON THE TRIAL MIXES

Batching of trial mixes was carried out according to their respective proportions, presented in Table 3.3. The concrete ingredients were mixed in a revolving drum type mixer for about three to five minutes to attain uniform consistency. The selfcompactibility of the trial mixes was evaluated using slump flow test, V-funnel test, and U-box test.

3.4.1 Slump Flow Test

The slump flow test was carried out according to ASTM C 143. Figure 3.1 shows the accessories used for the slump flow test. The dimensions of the frustum of cone used in this test are the same as that used for slump test (i.e. 200 mm bottom diameter, 100 mm top diameter and 300 mm height). The diameter of the concrete after allowing its full flow, as shown in Figure 3.2, was taken as slump flow value.

Figure 3. 1: Accessories for slump flow test.

Figure 3. 2: Measurement of slump flow

3.4.2 V-Funnel Test

V-funnel test was used to determine the filling ability (i.e., flowability) of SCC. The dimensions of V-funnel, similar to that used by Khayat et al. [1] were adopted, are shown in Figure 3.3.

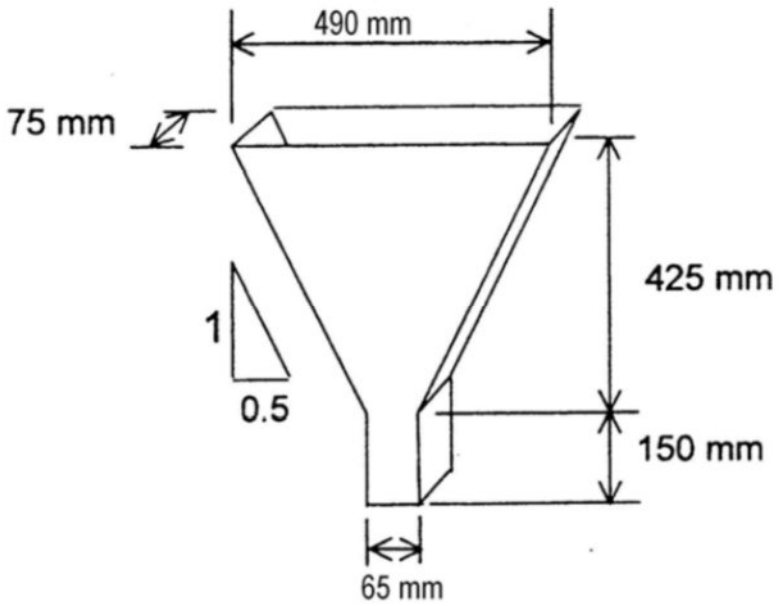


Figure 3. 3: Schematic diagram of V-funnel [1].

A V-funnel using the dimensions of Figure 3.3 was fabricated in the laboratory for this study. A photograph of the V-funnel is shown in Figure 3.4.

Figure 3. 4: Locally fabricated V-Funnel utilized to evaluate the segregation resistance of SCC.

Procedures for conducting the V-funnel test include the following steps:

1. The V-funnel is kept firm on the ground and the inside surfaces of the funnel are moistened and the trap door is kept open to allow any surplus water to drain.
2. About 12 liters of concrete is poured into V-funnel to fill it completely without compacting or tamping, while keeping the trap door closed and a bucket placed underneath.
3. After filling the V-funnel, concrete level is simply struck off with the top with a trowel.
4. After 10 sec of filling, the trap door is opened to allow concrete to flow out under gravity. The stopwatch is started when the trap door is opened, and the time taken for complete discharge of concrete from funnel is recorded as 'flow time'. As recommended, the whole test is to be performed within 5 minutes.

3.4.3 U-Box Test

The U-box test was used to measure the filling ability of the mixes. The apparatus used was similar to that used by Khayat et al. [1], which consists of a vessel that is divided by a middle wall into two compartments, as shown in Figure 3.5.

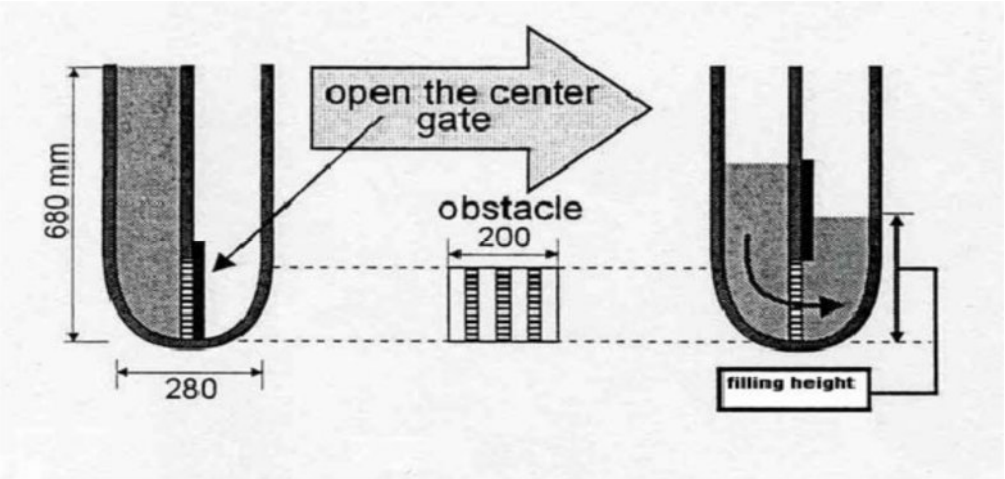


Figure 3. 5: Schematic representation of U-Box [1].

As shown in Figure 3.5, an opening with a sliding gate is fitted between the two sections. Reinforcing bars with normal diameters of 15 mm are installed at the gate with centre-to-centre spacing of 50 mm. This creates a clear spacing of 35 mm between the bars. Concrete filled in the left hand box is allowed to pass through this obstacle and to fill the right hand box. More will be the height of filling in the right hand box more will be the filling ability of the SCC mix.

A U-box apparatus was built in the laboratory using the dimensions suggested in EFNARC[18]. A view of the built apparatus is shown in Figure 3.6.

The procedure for conducting the U-box test includes the following steps:

1. The apparatus is set on firm ground, ensuring that the sliding gate can open freely and then be closed.
2. The inside surfaces of the apparatus are moistened, any surplus water is removed.
3. The left hand compartment of the apparatus is filled with about 20 liters of concrete.
4. After allowing concrete filled in the left hand compartment to stand for 1 minute, the sliding gate is then opened by lifting it up and concrete is allowed to flow upwards into the right hand compartment
5. After the concrete has come to rest, the height of the concrete is measured in both compartments at two places and the mean heights (say H1 as mean height in the left compartment and H2 as mean height in the right compartment) are calculated.
6. The 'filling height' is then calculated as H1- H2. Like the V-funnel test, the whole U-box test is also performed within 5 minutes.

Figure 3. 6: Locally fabricated U-box to evaluate the passing ability of SCC.

3.5 SELECTION OF SUITABLE MIX FROM TRIALS

The three key characteristics, filling ability, passing ability and resistance to segregation were assessed with different kinds of practical test methods and normally, a combination of test methods is used to classify a SCC mixture. Practical test methods to characterize the fresh properties of the trial mixtures are: slump flow, filling-ability and passing-ability. Results of the self-compactibility tests conducted on the trial mixes are presented in Table 3.7. Mixtures satisfying the SCC criteria were selected for further analysis.

Table 3. 7: Self-compactibility of trial mixtures.

	Self-compacting properties			
Mix designation	**Slump diameter*(mm)**	**U-box**(mm)**	**V-funnel*** (s)**	**Remarks**
NP 10	777	17	6	Accepted
NP 15	780	20	6	Accepted
NP 20	782	21	6	Accepted
NP 25	788	29	6	Accepted
NP 30	786	13	6	Accepted
NP 40	750	19	8	Rejected
NP 50	780	22	6	Rejected
LSP 10	750	18	8	Accepted
LSP 15	750	31	7	Rejected
LSP 20	750	28	8	Accepted
LSP 25	750	30	8	Rejected
LSP 30	750	28	8	Accepted
LSP 35	735	35	11	Rejected
LSP 40	730	25	10	Accepted
LSP 10C	720	18	10	Accepted
LSP 20C	705	22	10	Accepted
LSP 30C	700	23	10	Accepted
LSP 40C	700	26	10	Accepted
NP 10/LSP 10	690	16	6	Accepted
NP 20/LSP 10	710	24	7	Accepted

*Slump diameter value should be in the range of 650 to 800 mm [18].

** U-box value should be in the range of 0 to 30 mm [18].

*** V-funnel value should be in the range of 6 to 12 sec [18].

As observed from Table 3.7, all the trial mixtures satisfied the flowability criteria except for some of the mixes that were later dropped from further analysis.

CHAPTER FOUR

EVALUATION OF HARDENED PROPERTIES OF SELECTED SCC MIXTURES

In this chapter, the details of casting and testing the specimen prepared from the SCC mixtures for evaluating their hardened properties are presented. Whilst the number and size of the pores and capillaries in cement paste are related directly to its water-cement ratio, they are also related, indirectly, to the extent of water curing. Over time, water curing causes hydration products to fill, either partially or completely the pores and capillaries present, and, hence, help to reduce the porosity of the paste. With these facts in mind the concrete specimen were cured in water for a maximum period of 28 days under a constant temperature of 25°C. After curing, the concrete specimens were tested for compressive strength and durability properties. Durability tests on concrete specimens included:

1. Drying Shrinkage [ASTM C 531-95; BS 6319].
2. Sulfate Attack [ASTM C 856; BS EN 206-1].
3. Rapid Chloride permeability [ASTM C 1202].
4. Reinforcement Corrosion [ASTM C 876].

4.2 SPECIMENS

The details of specimens prepared to determine the compressive strength and durability properties are presented in Table 4.1.

Table 4. 1: Details of specimens and test to evaluate the properties of hardened concrete.

Test	Test Standard	Specimen used
1. Compressive Strength	ASTM C 39	100 x 100 x 100mm cube
2. Drying Shrinkage	ASTM C 531	40 x 40 x 160 mm prism
3. Sulfate Attack	ASTM C 1012	75 x 150 mm cylinder
4. Chloride Permeability	ASTM C 1202	100 x 200 mm cylinder
5. Reinforcement Corrosion	ASTM C 876	75 x 150 mm cylinder

4.2 SELECTED SCC MIX PROPORTIONS

Trial mixes satisfying self-compactibility criteria were selected as suitable mixes as described in Chapter 3.

4.3 CASTING AND CURING OF SPECIMENS

The specimens were cast and cured in a similar manner to that of the specimens for the trial mixes, described in the previous chapter.

4.4 TESTS

4.4.1 Compressive Strength

The concrete cube specimens, 100 x 100 x 100 mm, were prepared for evaluating the compressive strength. The compressive strength was determined according to ASTM C 39 after 7, 14, 28 and 90 days of water curing. The specimens were dried and tested under the

application of compressive load at a rate of 2.2 N/s. The load was applied until the specimen failed. The maximum load (kN) was noted. The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen (10^4 mm^2). The compressive strength machine is shown in Figure 4.1.

Figure 4. 1: Matest® compressive strength testing machine.

4.4.2 Drying Shrinkage

Prismatic concrete specimens measuring 40 x 40 x 160 mm were cast to determine the drying shrinkage of SCC. In order to measure the drying shrinkage, demec gauges were fixed on the specimen using an epoxy at a standard distance of 250 mm. The distance between the demec gauges was measured initially and at periodic intervals. The change in length with time was utilized to determine the drying shrinkage strain. Strains were recorded till the end of the testing period. This was done to generate enough points to plot the

shrinkage strain evolution curves. Figure 4.2 shows the specimens used for shrinkage measurements.

Figure 4. 2: Drying Shrinkage specimen

4.4.3 Rapid Chloride Permeability

The rapid chloride permeability of concrete specimens was determined according to ASTM C1202. This method determines the electrical conductance of concrete. A 50 mm thick disk was cut from the center of the 75 x 150 mm cylindrical specimen. The curved surface of the disk was coated with an epoxy coating to avoid evaporation of moisture during testing. The disk specimens were saturated with water under vacuum and kept saturated for about 24 hours. The saturated disk specimen was clamped between two cells and a potential difference of 60 V DC was maintained across them. The upstream cell was filled with 3%

sodium chloride (NaCl) solution and the downstream cell was filled with 0.3 M sodium hydroxide (NaOH) solution. A resistor was built into the circuit and the current was recorded at periodic intervals by connecting the resistor to a data acquisition system. The total charge passed, in coulombs is recorded over a six hour period. The whole test has to be performed at room temperature of 20 to 25^0C. Typical chloride permeability cells and specimens are shown in Figures 4.3 and 4.4, respectively.

Figure 4. 3: Rapid Chloride Permeability Test Cell.

Figure 4. 4: Specimens utilized for determining the Rapid Chloride Permeability.

4.4.4 Sulfate Resistance

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were prepared from each mixture. After 28 days of curing in water, the SCC specimens were immersed in 5% sulfate solution (2.5% from sodium sulfate salt and 2.5% from magnesium sulfate). The sulfate resistance was evaluated by visual examination and by determining the reduction in compressive strength according to ASTM C 267 after three and six months of exposure. The relative reduction in compressive strength due to sulfate attack, denoted as sulfate deterioration factor (SDF), was calculated using the following formula:

$$\text{SDF}=\frac{CSW-CSS}{CSW}*100$$

Where:

CSW = Average compressive strength of concrete specimens immersed in water; and,

CSS = Average compressive strength of concrete specimens stored in the sulfate solution.

4.4.5 Corrosion Resistance

The corrosion resistance of steel embedded in the SCC specimens was evaluated by exposing them to 5% sodium chloride solution. Reinforced SCC specimens, measuring 75 mm in diameter and 150 mm high, were prepared with a 12-mm diameter steel bar placed at the center. A cover of 25 mm was provided at the bottom. The reinforcing steel bars were coated with cement paste followed by an epoxy coating at the bottom of the bar and at the concrete-air interface to avoid crevice corrosion.

Reinforcement corrosion was monitored by measuring the corrosion potentials, according to ASTM C 876, and the corrosion current density by the linear polarization resistance method (LRPM) [63]. The corrosion measurements were conducted at regular intervals for 12 months.

Corrosion potentials: The corrosion potentials were measured using a saturated calomel reference electrode (SCE). The electrical lead from the reference electrode was connected to the positive terminal of a high impedance digital voltmeter while the steel bar in the concrete was connected to its negative terminal, as shown in Figure 4.5.

Figure 4. 5: Corrosion potential measurement setup.

Corrosion current density: The three electrode method was utilized to measure the resistance to polarization (Rp) using a Potentiostat/Galvanostat. The steel rod was connected to the working electrode terminal while a steel plate and a reference electrode were connected to the counter and reference electrode terminals of a Potentiostat/ Galvanostat, respectively. The setup is shown in Figures 4.6 and 4.7.

Figure 4. 6: Corrosion current density measurement setup.

Figure 4. 7: Pictorial view of the electrodes.

The steel was polarized to ± 20 mV of the corrosion potential at a rate of 6 mV/min and the resulting current between the counter and the working electrodes was measured. R_p was determined as the slope of the current-potential curve. Corrosion current density (I_{corr}) was evaluated using the following relationship [24]:

$$I_{corr} = \frac{B}{R_p}$$

Where:

I_{corr} = Corrosion current density, $\mu A/cm^2$

Rp = Resistance to polarization, ($\Delta E / \Delta I$), $\Omega.cm^2$

$$B = \frac{\beta_a * \beta_c}{2.3(\beta_a + \beta_c)}$$

Where: β_a and β_c are the anodic and cathodic Tafel constants, mV/decade, respectively.

The Tafel constants are normally obtained by polarizing the steel to ± 250 mV of the corrosion potential (Tafel plot). However, in the absence of sufficient data on β_a and β_c, a value of B equal to 26 mV for steel in active condition and 52 mV for steel in passive condition is often used [64]. Lambert et al. [65] have reported a good correlation between corrosion rates determined using these values and the gravimetric weight loss method.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 COMPRESSIVE STRENGTH

The compressive strength of SCC specimen is summarized in Table 5.1.

Table 5. 1: Compressive strength of SCC Specimens.

Mix designation	Compressive strength (MPa)				
	3 Days	7 Days	14 Days	28 Days	90 Days
NP 10	37.72	42.76	51.65	51.94	56.72
NP 15	32.20	41.86	47.01	47.32	60.88
NP 20	30.70	37.74	42.09	44.65	61.41
NP 25	28.84	31.51	39.32	44.20	59.19
NP 30	24.56	32.59	35.66	44.16	57.98
LSP 10	65.73	69.65	70.02	78.21	80.42
LSP 20	49.91	56.07	62.27	68.34	71
LSP 30	40.09	57.92	58.64	67.88	70.25
LSP 40	36.78	53.24	58.35	67.33	67.56
LSP 10C	47.78	51.80	56.24	56.81	62.86
LSP 20C	25.89	29.84	34.32	45.67	50.19
LSP 30C	26.53	31.85	38.00	46.02	49.35
LSP 40C	24.80	24.84	32.71	35.18	40.52
NP 10/LSP 10	40.90	49.30	60.76	61.86	75.50
NP 20/LSP 10	45.50	53.20	59.24	60.51	67.91
FA 20/LSP 10	43.31	49.78	50.78	60.96	69.13

5.1.1 NP Cement Concrete

The compressive strength of SCC with NP is plotted in Figure 5.1. As seen from these data, the early age compressive strength decreases as the quantity of NP increases. The reduction in strength was considerable at 3, 7, 14, and 28 days, which is an indication that NP

in the mixture has not yet fully reacted with the calcium hydroxide. The decrease in the strength may also be attributed to reduction in the quantity of cement. The difference 28 and 90-day strength was significant due to retardation in the pozzolanic reaction. It may also be noticed from the data in Figure 5.1 that the optimum quantity of NP to give the highest strength is 20 %. After 90 days of water curing, the compressive strength of 10-30 % NP SCC was in the range of 63 – 56 MPa.

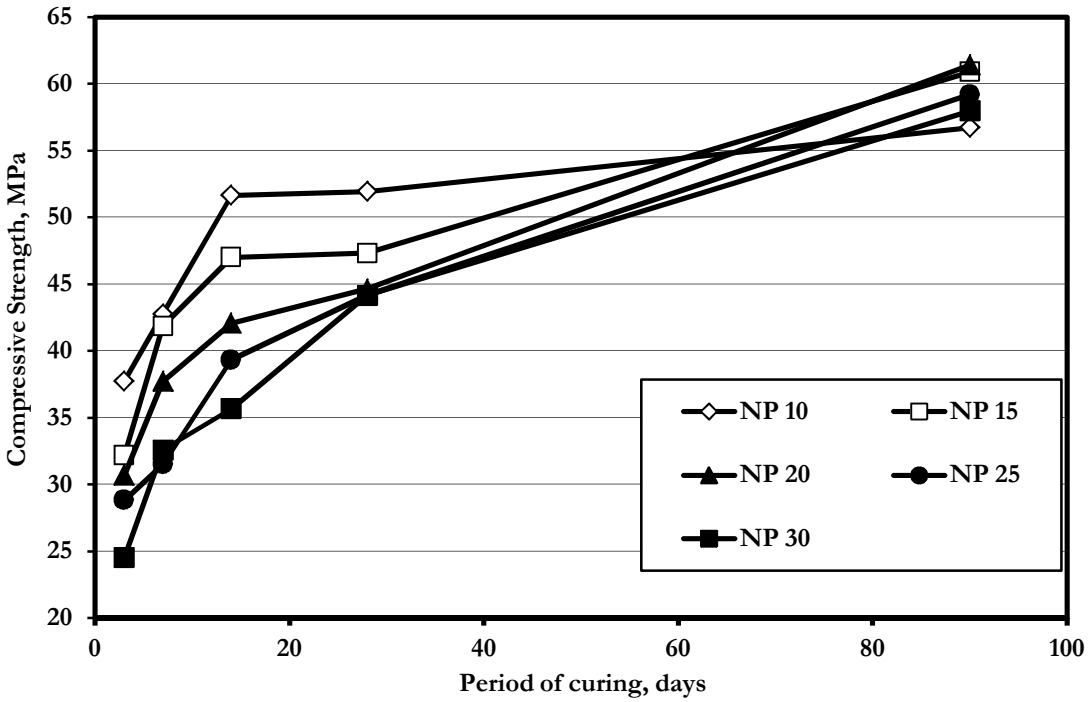


Figure 5. 1: Compressive strength of SCC with NP.

Studies performed earlier revealed that cements including NP may have a lower strength because the grinded clinker grains move away from each other [66]. However, after a long period, as the pozzolan grains start to react, it can be seen that this strength difference will decrease and the next factor of concern affecting the strength would then be the degree of filling the micro gaps.

Many researchers have reported that the strength of NP is slow in the early curing period [67, 68], because the overall pozzolanic reaction was slow. However, strength was increased, exceeding the reaction by a large amount within few weeks. The decrease in strength could also be attributed to the fact that larger replacement leads to a surplus of the small-sized fraction which begins to move apart cement grains, causing unpacking of the system and thus leading to a considerable decrease in the strength of the system [67].

The other aspect of the compressive results is that although the quantity of NP is raised to about 30% (by mass), the compressive strength is more than 45 MPa, a highly useful value. This situation indicates that NP can be used in large quantities in SCC [69]. This provides the needed strength and durability. Mehta [70] has reported that blended Portland cements containing 10-30% NP produced similar or higher compressive strength than the reference Portland cement. Moreover, it possessed much better durability to alkali-silica expansion and sulfate attack [71]. The use of about 30 % NP in SCC is beneficial as it not only reduces the cost but also decreases the heat of hydration in addition to an enhancement in the durability.

5.1.2 LSP Cement Concrete

LSP was mixed with the concrete via two ways; addition to the cement and replacement of a portion of the cement in different percentages. For instance, LSP 10 denotes addition of 10% LSP to the Portland cement (replacement for coarse aggregate) while LSP 10C denotes replacement of 10% of the Portland cement with LSP.

Figure 5.2 shows the compressive strength development of SCC with LSP. From Figure 5.2, rapid early strength gain was noticed between 3 and 7 days for concrete with LSP addition to Portland cement. The strength continue to increase after the 7 days but at a slow

rate compared to that experienced in the early days of strength development. The highest recorded compressive strength (78MPa) at 28 days was with the lowest LSP addition (10%) and the least (67MPa) was recorded with the highest LSP addition (40%).

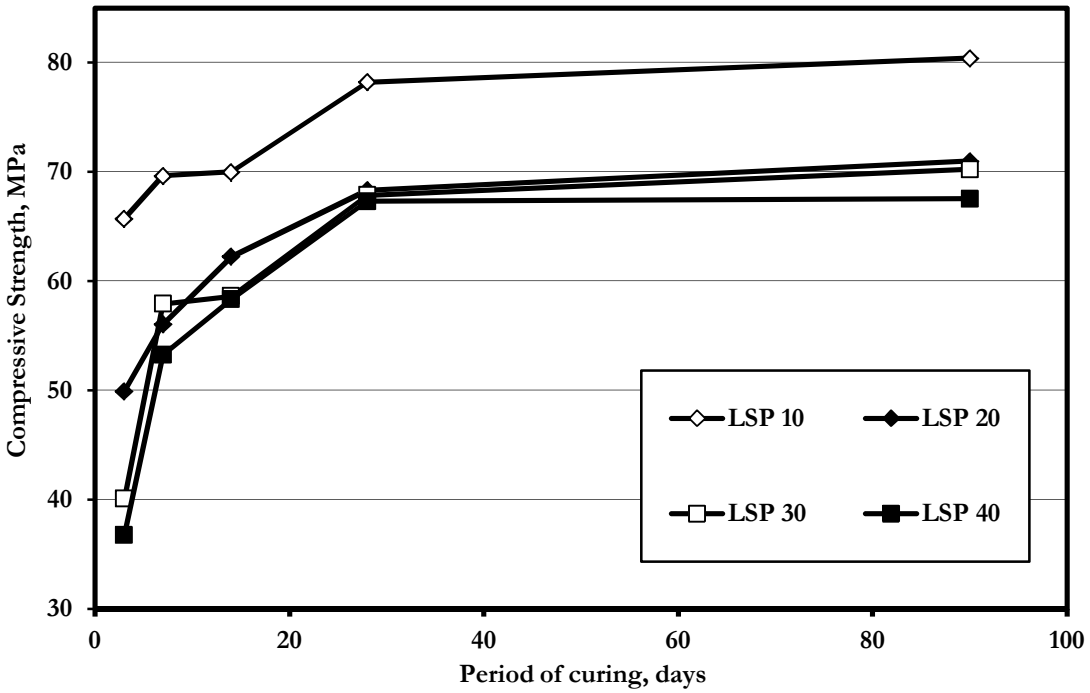


Figure 5. 2: Compressive strength of SCC with LSP addition to cement.

The performance of LSP addition to Portland cement has been widely studied in pastes, mortars and concrete [72]. The addition of LSP causes an acceleration in the hydration of the clinker minerals, especially C_3S [73]. It was also reported by Bonavetti et al [72] that the rate of acceleration is higher when the amount and fineness of the LSP is increased. This effect is more pronounced in the early ages. In general, LSP improves the hydration rate of cement compounds and consequently increases the strength at early ages [74]. This in fact is due to, as mentioned by several authors, improvement in setting kinetics, reduction in dormant period which as a result led to acceleration in the hydration process [75-78]. Kadri et al [79] state that the filler particles promote sites of heterogeneous

nucleation to precipitate more or less crystallized hydrates and in this way accelerate the hydration. Further, the additional surface area provided by the LSP may provide sites for the nucleation and growth of hydration products, generally enhancing the achieved hydration [80]. Finally, the presence of LSP contributes to cumulated heat and heat released than for mixtures with cement and water [81]. However, it should be noted that the compressive strength of 20 to 40 % LSP is lower than the SCC with 10 % LSP. Also, the difference in the strength of 20, 30 and 40 % LSP was not much.

Figure 5.3 shows the compressive strength development in the SCC with LSP used as a replacement of cement. There is an indication of strength development in all the mixtures with the period of curing. This increase in compressive strength despite the weak cement-aggregate bond caused by higher filler, can be explained considering the pore-filling effect of fine-grounded limestone powder [83]. The highest compressive strength of 57MPa at 28 days was measured in SCC with 10 %, and the least strength of 35MPa was noted at in 40 % LSP cement. At 90 days, not so much difference was measured in their compressive strengths compared to 28 days strength.

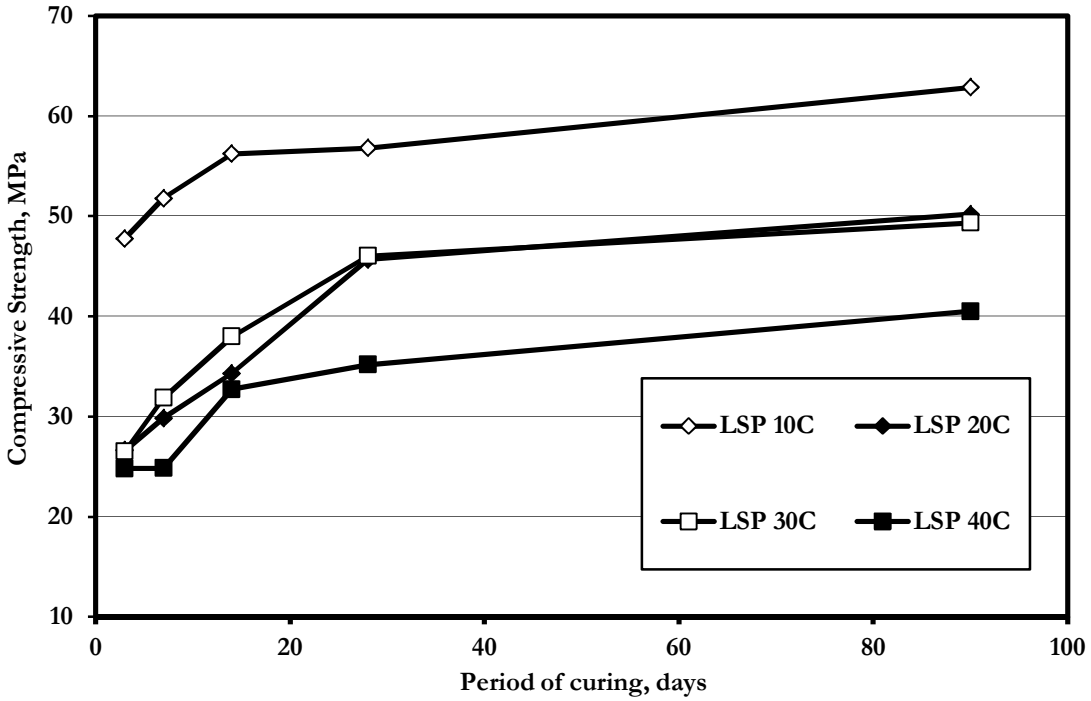


Figure 5. 3: Compressive strength of SCC with LSP replacement of cement.

Generally, it should be mentioned that for second set of experiments where some percentages of the Portland cement was replaced by LSP, early strength gain was also experienced but with a much lower strength value compared to when LSP was added to the Portland cement. This is an indication that there is a different behavior in the compressive strength of LSP addition to Portland cement and its replacement of cement. Since reactive Portland cement is being replaced with a relatively inert LSP, it would be expected that some decrease in compressive strength would occur in concretes with LSP replacement for cement. In literature, LSP was neither described as cementitious nor a pozzolanic material. Therefore, it is accepted that LSP contributes little to the strength of mortar [82]. The data in Table 5.1 showed that at 10% replacement of cement, there is a rapid early strength increase up to a period of 3 days and it continue to increase until 57MPa and 63MPa at 28 and 90 days respectively. A sharp decrease in compressive strength was noticed from 10% to 20%

replacement of cement with LSP, from 47.8MPa to 26.6MPa, respectively. This decrease may be due to the fact that the paste was not enough to coat all the aggregates which would serve as a bonding substance between the aggregate bond and by extension created a weak bond in the cement-aggregate interface. This weak cement-aggregate led to a decrease in compressive strength for higher LSP content (more than 10%).

The compressive strength of mineral admixtures, NP and LSP combined in different proportions were also tested so as to harness the inherent advantages in both the materials. Three mix proportions were used for this test, two of which were prepared with varying NP (10 and 20% replacing cement), designated as NP10/LSP10 and NP20/LSP10, while LSP was made constant at 10 % added to cement in both cases. The third mix proportion was prepared by replacing 20% of cement with fly ash (FA) and adding 10% of LSP to the cement, designated as FA20/LSP10. This acts as a control, to compare the behavior of the testing materials (NP and LSP) against a tested and standard material, FA. From the data in Table 5.1, it is clear that the compressive strength of the three mix proportions compare favorably with their strength value in very close range. NP10/LSP10 gave the highest early and later strength followed by FA20/LSP10 and then NP20/LSP10. This is expected because there is a combination of pozzolanic property of NP and the pore-filling capability of LSP in the concrete. The behavior of these three mix proportions are depicted in Figure 5.4.

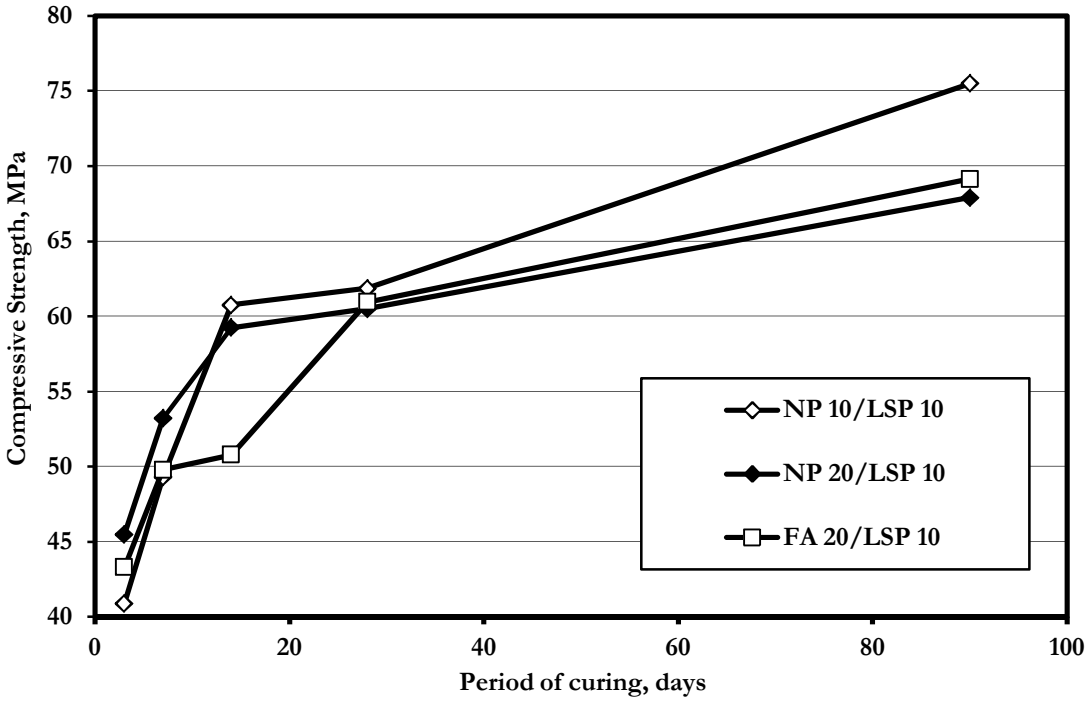


Figure 5. 4: Compressive strength of SCC with mixture of NP and LSP.

5.2 RAPID CHLORIDE PERMEABILITY

The rapid chloride permeability test was conducted in accordance with ASTM C 1202 after 28 days of curing. The total charge passed through the concrete specimens was determined and used to evaluate the chloride permeability of each concrete mixture. The chloride permeability results for SCC specimens after 28 days of water curing are presented in Table 5.2. The chloride permeability of SCC specimens prepared using NP was 'moderate' according to ASTM C 1202 criteria. This permeability property from NP could be attributed to the good microstructure of the concrete due to the formation of more C-S-H gels filling the pore and making it dense.

Table 5. 2: Chloride permeability of SCC specimen

	Mixture Details	Chloride Permeability, Coulombs	
		Charge passed	Classification
1	NP 10	3331	Moderate
2	NP 15	2628	Moderate
3	NP 20	2569	Moderate
4	NP 25	2966	Moderate
5	NP 30	3075	Moderate
6	LSP 10	2923	Moderate
7	LSP 20	3306	Moderate
8	LSP 30	5774	High
9	LSP 40	5656	High
10	LSP 10C	5097	High
11	LSP 20C	5380	High
12	LSP 30C	6130	High
13	LSP 40C	6450	High
14	NP 10/LSP 10	3714	Moderate
15	NP 20/LSP 10	3073	Moderate
16	FA 20/LSP 10	2842	Moderate

The incorporation of pozzolanic materials improves the resistance to chloride penetration of mortar as confirmed by many researchers [84, 85]. The rapid chloride ion permeability of concrete containing pozzolanic materials was lower than that of plain cement concrete [86]. This may be related to the refined pore structure of these concretes and their reduced electrical conductivity [87]. Chindaprasirt [85] also proposed the reason for the lower chloride ion penetration as due to the reduction in the average pore size of paste and improvement of the interfacial zone.

With LSP, both replacement of and addition to Portland cement, a mixed behavior was recorded, for instance, 10 and 20% addition of LSP proved moderate in chloride permeability but as LSP increased, high permeability was recorded due to high passage of

chloride ions. Also, for replacement with LSP, the permeability was high. The higher chloride ion permeability of the concrete containing LSP could be said to be related to higher level of OH^- ions present in the pore fluid of the concrete made with LSP. Andrade [88] proposed that the OH^- ions present in the pore fluid acts as supporting electrolyte and are responsible for the transportation of a significant amount of charge during chloride ion permeability because of its higher ionic conductivity than the other ions present in the pore fluid (Na^+, K^+ and Ca^{2+}). On the other hand, the higher chloride ion permeability could also be attributed to the porous and connected paste-aggregate interfacial transition zone (ITZ) associated with LSP addition.

Bonavetti et al [72] reported that the penetration of chloride ions increased from 43% to 114% for concrete containing 10% and 20% LSP, respectively. The addition of limestone in concrete increases the chloride ion diffusion depending on the level of addition [72, 89].

5.3 SULFATE RESISTANCE

5.3.1 Visual Examination

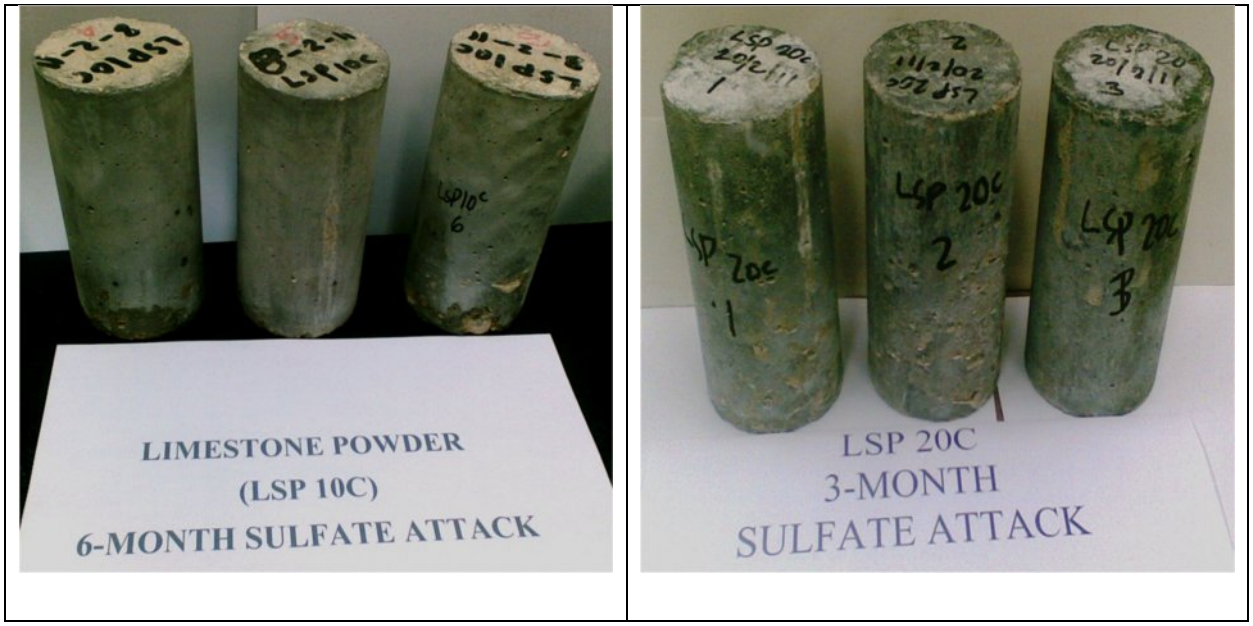
A thorough visual examination was carried out on all the mixtures after three and six months of exposure to sulfate solution, to evaluate the visible signs of softening, cracking and spalling in the SCC specimen. Sulfate attack on concrete is primarily attributed to sodium, magnesium and calcium sulfate salts. Due to limited solubility of calcium salts in water at normal temperature (approximately 1400mg/l SO_4^{2-}), sulfate attack is then normally ascribable to presence of $MgSO_4^{2-}$ and $Na_2SO_4^{2-}$. Figures 5.5 through 5.7 show typical SCC specimens subjected to sulfate attack after three and six months immersion in 2.5 % magnesium sulfate and 2.5 % sodium sulfate solutions.

(a) (b)

Figure 5. 5: (a) NP10 specimen after three months and (b) six months of exposure to the sulfate solution.

(a) (b)

Figure 5. 6: (a) NP 30 specimen after three months and (b) six months of exposure to the sulfate solution.



(a) (b)

Figure 5. 7: (a) SCC specimen showing spalling at the corners and (b) another SCC specimen showing exposure of the concrete due to softening and break-off.

Results of the visual examination revealed that most of them, especially the NP SCC specimens, were in good condition, in that there was no evidence of severe spalling on the surface of the specimen but a little at the corners. But for LSP SCC specimens, both addition and replacement of cement, small amount of spalling was seen on the edges and corners in addition to very noticeable softening of the concrete's curved surface. Figure 5.7 shows a set of LSP SCC specimens that underwent softening on their curved surfaces and spalling at the edges. The visual examination of SCC specimens stored in the magnesium and sodium sulfate solutions for six months as shown in Figures 5.5 to 5.7 revealed that the intensity of the combined damage by magnesium and sodium sulfate attack was relatively more in specimens prepared with LSP compared to those prepared with NP. An improved appearance was noticed with specimen containing both materials (LSP and NP). An inspection table showing visual inspection observation is shown in Table 5.3 below.

Table 5. 3 Visual observations of SCC specimens

Mix #	Mix details	Observations	
		3 -Month Exposure	6-Month Exposure
1	NP10	No spalling	No deterioration but little edge softening
2	NP15	No spalling	No deterioration but little edge softening
3	NP20	No spalling	No deterioration
4	NP25	No spalling	No deterioration
5	NP30	No spalling	No deterioration
6	LSP10	No spalling	Little edge softening and curved surface exposure
7	LSP20	No spalling	Little edge softening and curved surface exposure
8	LSP30	No spalling	Little edge softening and curved surface exposure
9	LSP40	No spalling	Little edge softening and curved surface exposure
10	LSP10C	Little spalling	Edge softening and some aggregates exposure at base
11	LSP20C	Little spalling	Edge softening and some aggregates exposure at base
12	LSP30C	Little edge spalling	No visible surface exposure but a little on the edge
13	LSP40C	Little edge exposure	No visible surface exposure but a little on the edge
14	NP10/LSP10	No spalling	No spalling
15	NP20/LSP10	No spalling	No spalling
16	FA20/LSP10	No spalling	No spalling

5.3.2 Compressive Strength Loss

The compressive strength development of SCC specimens prepared with NP and exposed to sulfate solution up to 6 months is presented in Figures 5.8 and 5.9. For the 3-month exposure, comparing with the 28-day compressive strength, the residual compressive strength of the specimens increased until after NP20 where it started to decrease. This buttresses the fact that 20 % replacement of cement is beneficial from sulfate attack

perspective. The improvement in strength in specimens NP10, NP15 and NP20 at this period of exposure could be attributed to the movement of sulfate ions into mortars and possible crystallization of the sulfates in the pores of the mortars.

For 6-month exposure, all the SCC specimens underwent a decrease in compressive strength except for NP20 SCC specimen that maintained its increment in strength, although it was minimal. The reduction in the strength could be related to the formation of ettringite which is dependent on the amount of C_3A and $Ca(OH)_2$ present in SCC. The higher the cement content, the higher the amount of ettringite formed which leads to the saturation of the pores and it exerts pressure in the pore capillaries which then results in severe damage and strength loss [90]. As the amount of cement replaced by NP increases in the SCC specimen, the likelihood to form enough ettringite to cause damage decreases, then strength continues to increase. But after a certain optimum, NP20 as evident in Figure 5.9, the strength takes a down turn, which is an indication of weakness in its matrix because of reduction in binding strength of the cementitious material.

Several works in the past have pointed out the merits of using NP in resisting the damaging effects of sulfate ions. Sideris et al [91] revealed in his works that mixtures produced with natural pozzolans had a relatively good sulfate resistance only when the pozzolan replaced cement at high proportions. Kevser [92] also reported that the use of natural pozzolan improves the sulfate resistance of cements due to the CH reduction in mortars.

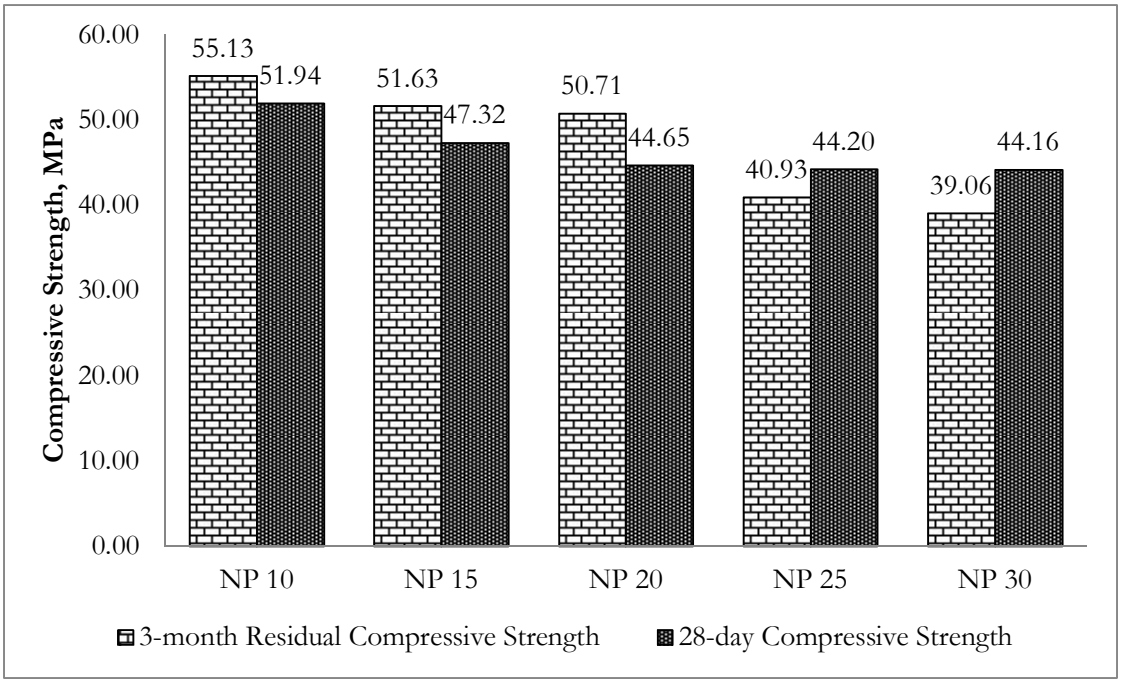


Figure 5. 8: Comparison between 28-day and residual compressive strength of NP SCC specimens after 3-month of sulfate exposure.

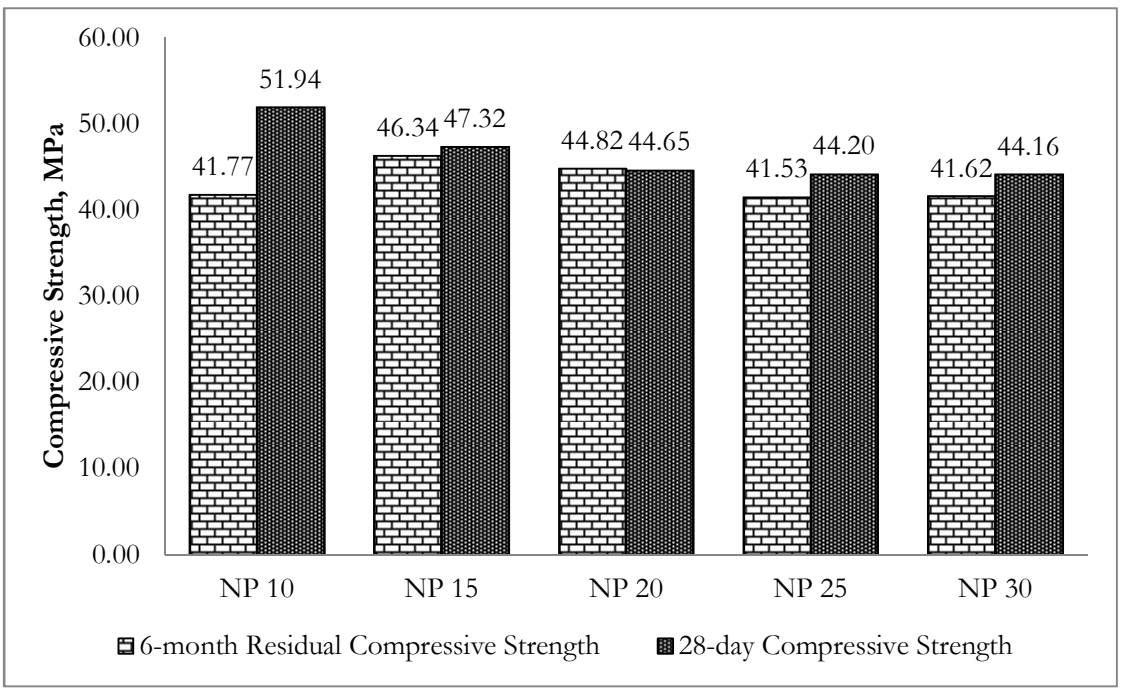


Figure 5. 9: Comparison between 28-day and residual compressive strength of NP SCC specimens after 6-month of sulfate exposure.

For the second set of SCC specimen, where LSP is added to cement, the residual compressive strength of the entire specimens, except LSP10 SCC specimen, increased compared to 28-day compressive strength for the 3-month sulfate exposure as displayed in Figure 5.10. But for the 6-month exposure as also shown in Figure 5.11, there was a decrease in compressive strength for the entire SCC specimens. This could be attributed to the weak capillary porosity, which allows the ingress of sulfate ions which caused deleterious effects on the SCC matrix which decrease the compressive strength. Another factor could be the increase in pH of the matrix due to the addition of LSP.

According to what is currently known, the incorporation of a large amount of limestone filler in cement, mortar or concrete could affect its durability, especially, chloride ingress, carbonation, sulfate resistance and fire resistance. As regards external sulfate attack, cementitious materials with limestone filler are more susceptible to thaumasite formation [93]. The negative effects of limestone addition on strength can be attributed to sulfate related microstructural changes [90]. However, it should be noted that thaumasite is formed at low temperature and consequently lime-cements are susceptible to such reactions in cold environments.

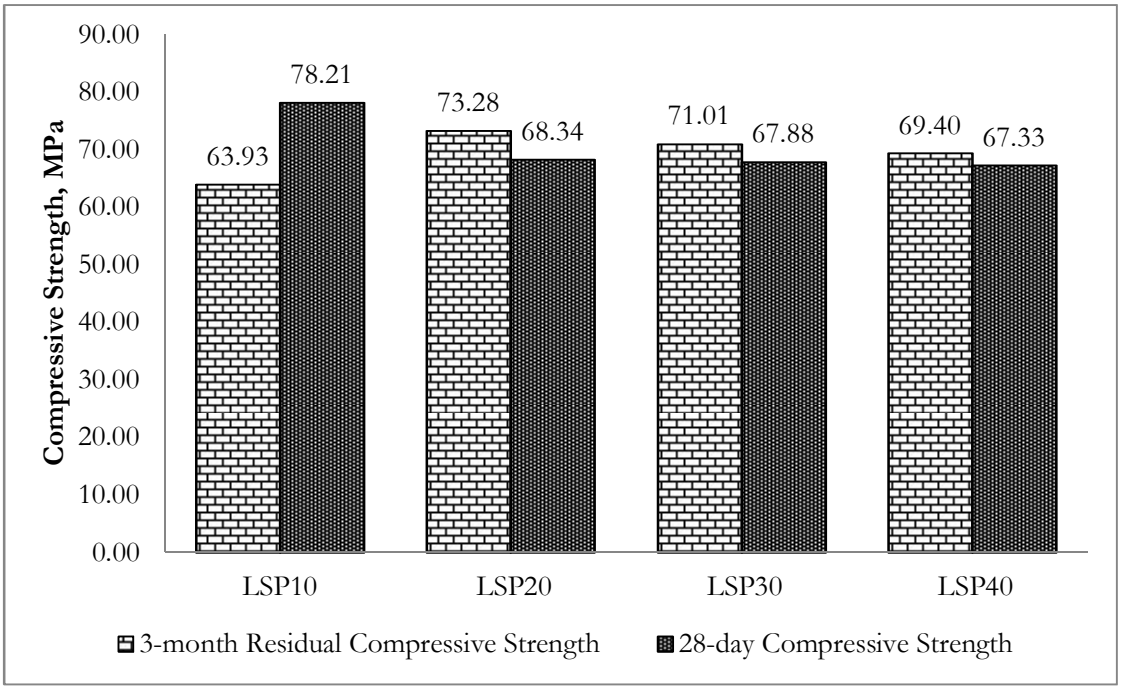


Figure 5. 10: Comparison between 28-day and residual compressive strength of LSP SCC specimens after 3-month of sulfate exposure.

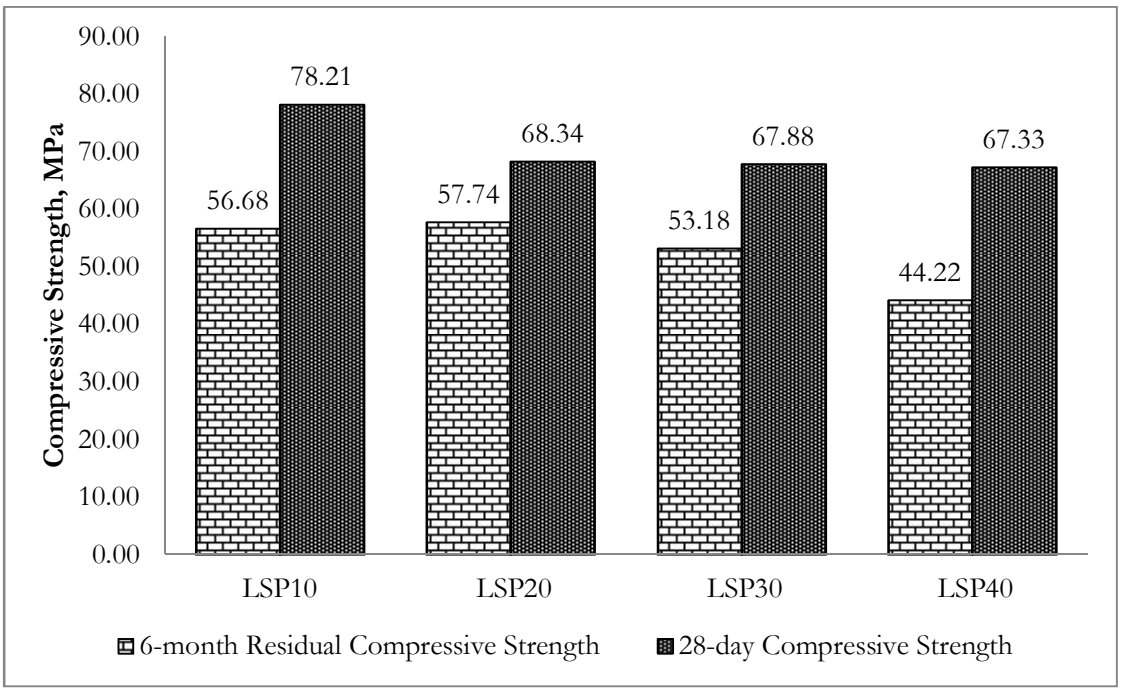


Figure 5. 11: Comparison between 28-day and residual compressive strength of LSP SCC specimens after 6-month of sulfate exposure.

For the third set of SCC specimens, where LSP is replacing cement, the residual compressive strength for the 3-month exposure is less than 28-day compressive strength as depicted in Figure 5.12, which is an indication of weak microstructure typical of limestone incorporated specimens. For the 6-month exposure, Figure 5.13 shows a further reduction in the compressive strength. Further, it is confirmed that the values of strength loss greatly depend on the replacement levels of limestone filler, especially at later exposure periods [94].

These experimental results imply the undesirable effect of limestone filler on the characteristic of compressive strength of mortar specimen under sulfate attack orienting from sodium and magnesium sulfate solutions, and are in agreement with those reported by other researchers [95, 96]. The ASTM C150-04 standard has recently permitted up to 5% of limestone filler ($CaCO_3$ < 70%) by mass in their cement types, so that physical and chemical requirements are met [93].

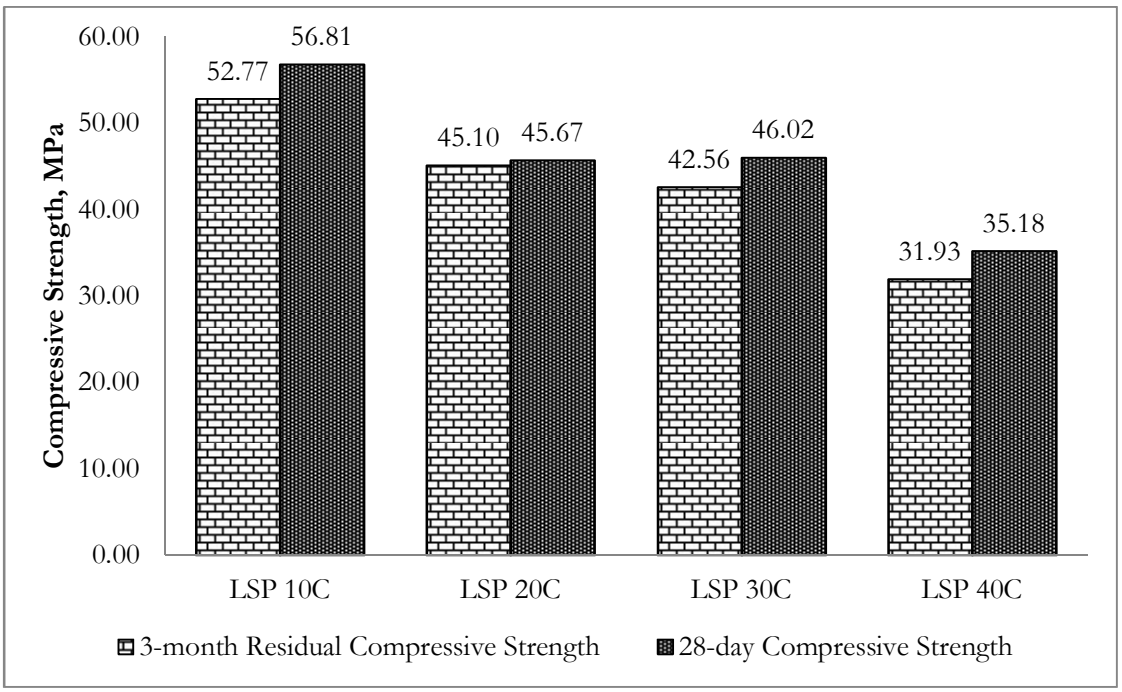


Figure 5. 12: Comparison between 28-day and residual compressive strength of LSPC SCC specimens after 3-month of sulfate exposure.

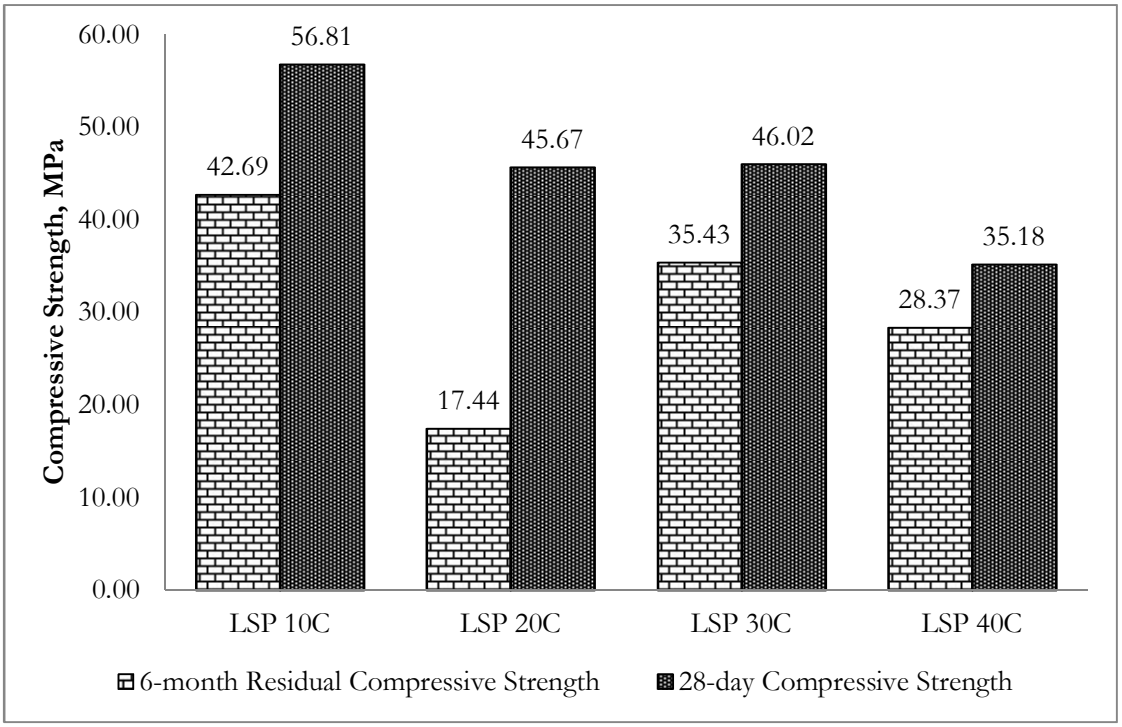


Figure 5. 13: Comparison between 28-day and residual compressive strength of LSPC SCC specimens after 6-month of sulfate exposure.

The SCC blend specimens, NP10/LSP10 and NP20/LSP10 were also subjected to sulfate attack. For 3-month exposure, NP10/LSP10 performed better compared to NP20/LSP10 in exposure to sulfate solution despite comparable 28-day compressive strength. The rate of strength loss in NP20/LSP10 SCC specimen was higher than the loss experienced in NP10/LSP10 SCC specimen as shown in Figure 5.14 and 5.15. This could be attributed to a stronger matrix and a lower capillary pores in NP10/LSP10. Also worthy of mention is the performance of FA20/LSP10 SCC specimen, in that the performance was favorable with increase in the compressive strength from 3 months to 6 months of exposure, though less than the 28 days compressive strength.

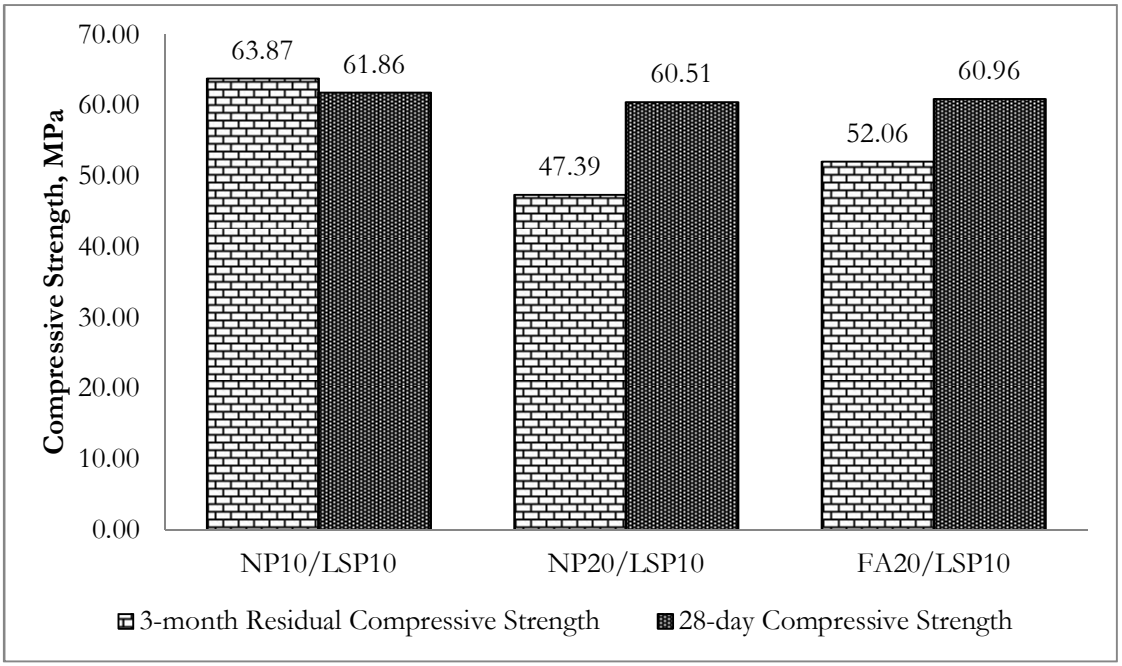


Figure 5. 14: Comparison between 28-day and residual compressive strength of two-admixture SCC specimens after 3-month sulfate attack exposure.

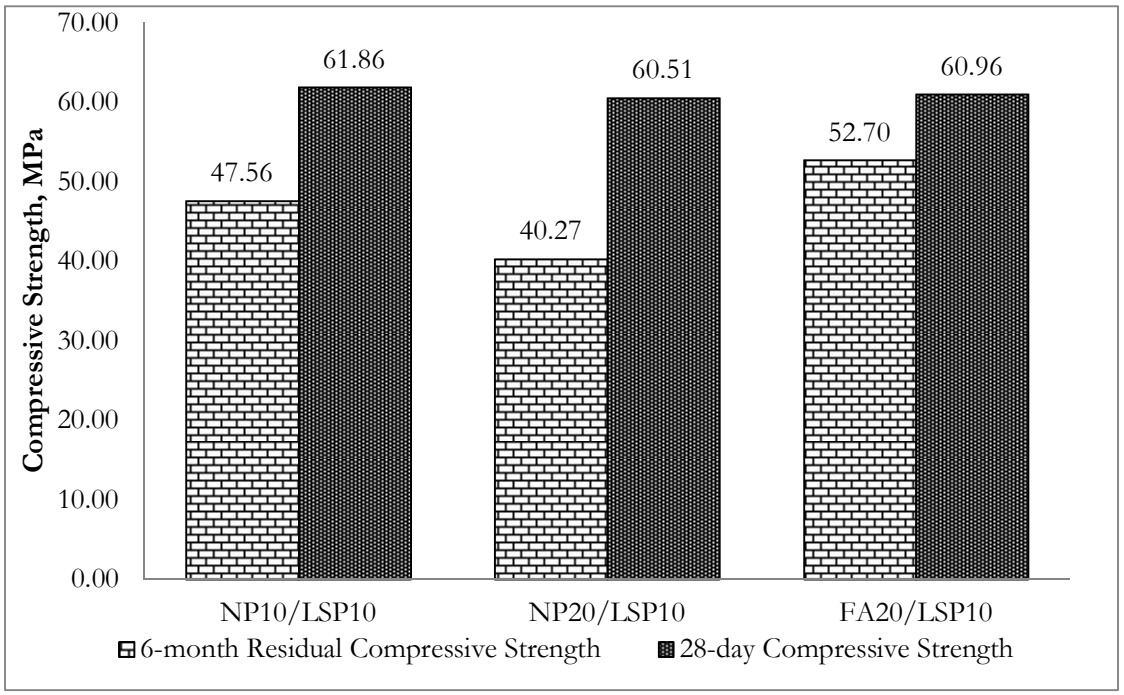


Figure 5. 15: Comparison between 28-day and residual compressive strength of two-admixture SCC specimens after 6-month sulfate attack exposure.

5.4 DRYING SHRINKAGE

5.4.1 SCC with NP

The drying shrinkage strain measurements recorded for SCC NP specimens in a period of 268 days are plotted in Figure 5.15. As expected, the drying shrinkage strain increased rapidly initially up to 180 days and, thereafter, the change in the drying shrinkage strain was not that significant. After 268 days of exposure, there was no significant increase in the shrinkage strain. The change in the behavior of the different percentages of NP is correlated in Figure 5.15. From these data, it can be noticed that the maximum shrinkage was experienced in the SCC specimen with the highest percentage of NP and the minimum shrinkage with the specimen with the lowest percentage of NP. The trend is well reported in research papers, chiefly of which are the works of Sawan [97], Itim [98] and Shannag [68]. As the amount of NP added increases, the volume of mortar in the concrete mixture increases, thus there was an increase in the drying shrinkage of mortar due to loss of water. The increase in drying shrinkage in SCC specimens can also be ascribed to high volume of fine aggregate fillers, low volume of coarse aggregates and ultimately high cement content.

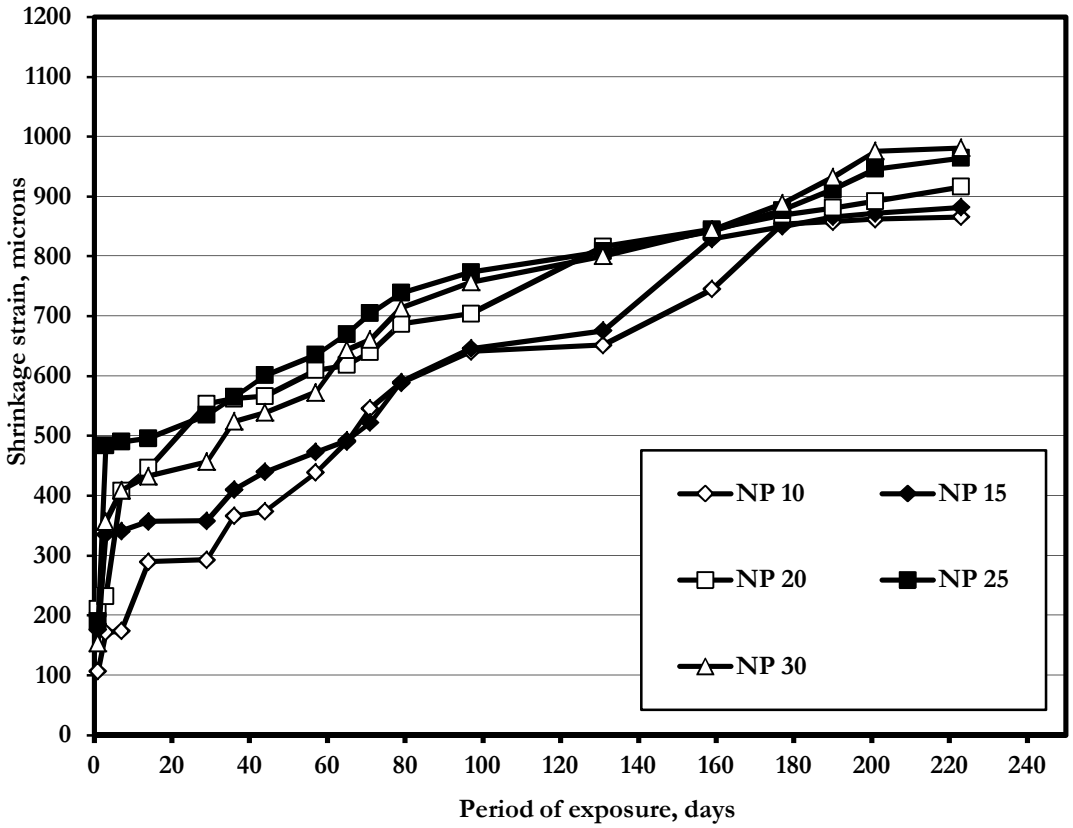


Figure 5. 16: Average drying shrinkage strain-time plot for NP SCC specimens.

5.4.2 SCC with LSP (Limestone addition to cement)

The drying shrinkage strain measurements recorded for SCC LSP specimens in a period of 238 days are plotted in Figure 5.16. As expected, the drying shrinkage strain increased rapidly initially up to 120 days and, thereafter, the change in the drying shrinkage strain progressed in a slow steady manner. The shrinkage strain is very much dependent on the percentage of LSP, as LSP addition increases, shrinkage strain of SCC specimens increase.

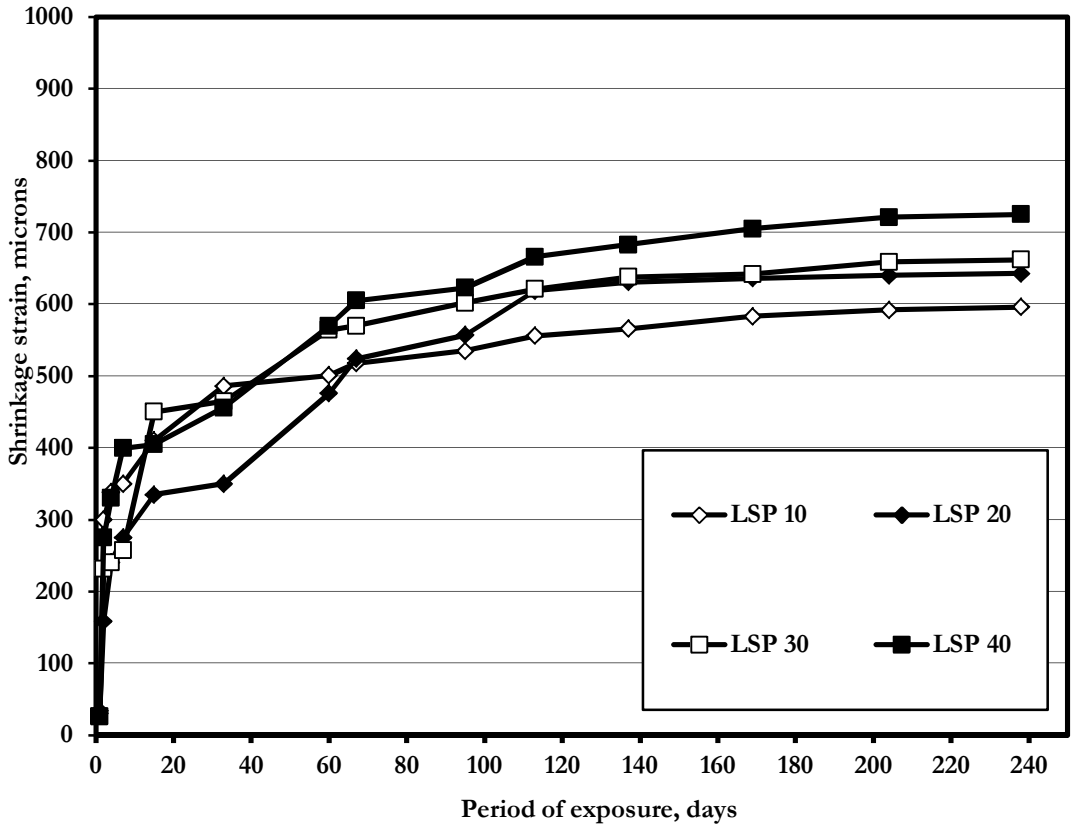


Figure 5. 17: Average drying shrinkage strain-time plot for LSP SCC specimens.

5.4.3 SCC with LSPC (Limestone replacement to cement)

The drying shrinkage strain measurements recorded for SCC LSPC specimens in a period of 177 days are plotted in Figure 5.17. As expected, the drying shrinkage strain increased rapidly initially up to 52 days and, thereafter, the change in the drying shrinkage strain was not rapid. The shrinkage strain is very much dependent on the percentage of LSP, as LSP replacement increases, shrinkage strain of SCC specimens increases.

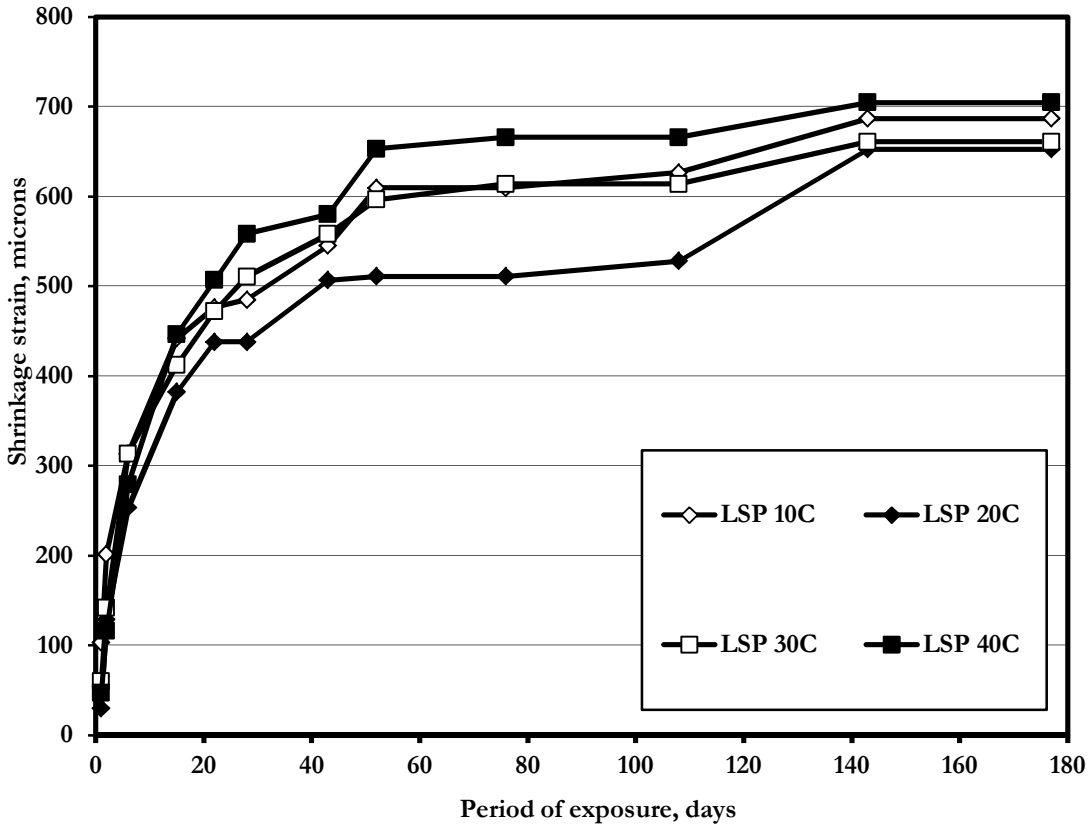


Figure 5. 18: Average drying shrinkage strain-time plot for LSPC SCC specimens.

5.4.4 SCC blend between NP and LSP

The drying shrinkage strain measurements recorded for SCC with blend of NP and LSP i.e., NP10/LSP10 and NP20/LSP10, are plotted in Figure 5.18. From the plot, it was noticed that for the same numbers of days, the shrinkage strain in NP20/LSP10 specimen is higher than that of NP10/LSP10. This could simply be as a result of higher percentage of NP in the specimen with the higher strain, since LSP is constant in both specimens. This higher percentage of NP gave more paste and by extension more water to lose and thus more shrinkage strain.

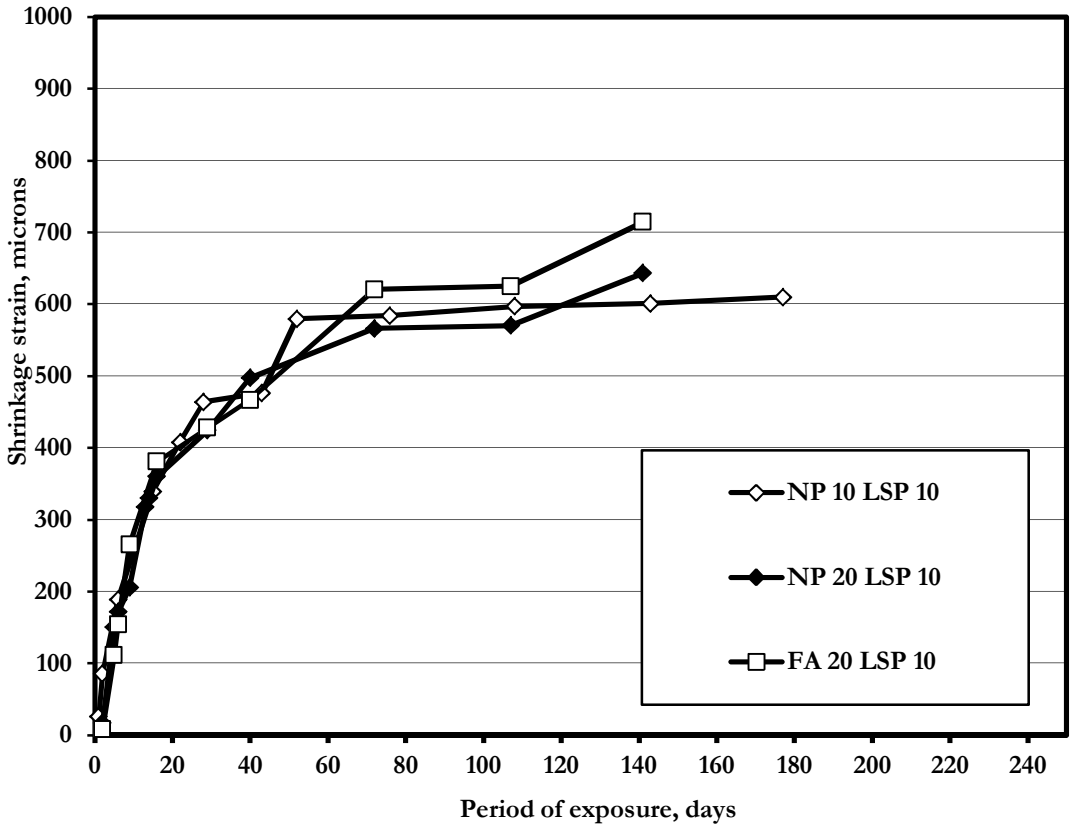


Figure 5. 19: Average drying shrinkage strain-time plot for blend of NP and LSP SCC specimens.

5.5 REINFORCEMENT CORROSION

5.5.1 Corrosion Potentials

SCC with Natural Pozzolan

The variation of average corrosion potentials with time of exposure to 5% NaCl solution are shown in Figure 5.19. The corrosion potentials decreased with an increase in the period of exposure. The corrosion potentials curve crossed the ASTM C 876 threshold value of -270 mV SCE after different days of exposure which represents the time to initiation of reinforcement corrosion.

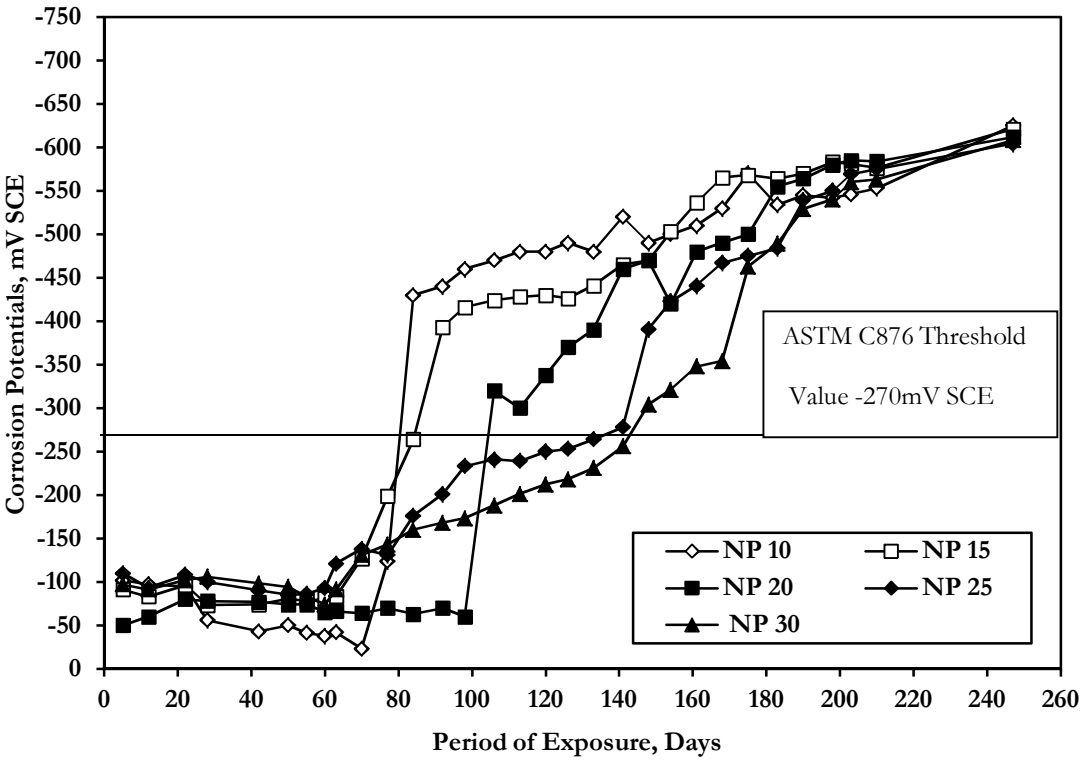


Figure 5. 20: Corrosion potentials on steel in NP SCC specimens exposed to 5% NaCl solution.

The corrosion potential curves for NP10 and NP15 specimens crossed the ASTM C 876 threshold value of -270 mV SCE after 84 and 92 days of exposure, respectively, while in NP20, NP25 and NP30 specimens, the corrosion potentials curves crossed the ASTM C 876 threshold value of -270 mV SCE after 106, 141, and 148 days of exposure, respectively which means that the time to initiation of reinforcement corrosion in these reinforcement bars increases with an increase in the percentage of NP in the SCC specimen.

SCC with Limestone Powder Replacing Cement

The variation of average corrosion potentials with exposure time of reinforcement bar present in LSPC SCC specimens immersed in 5% NaCl solution are shown in Figure

5.20. From the Figure, there is a clear indication of a decrease in corrosion potential as the percentages of the LSP replacing cement increases.

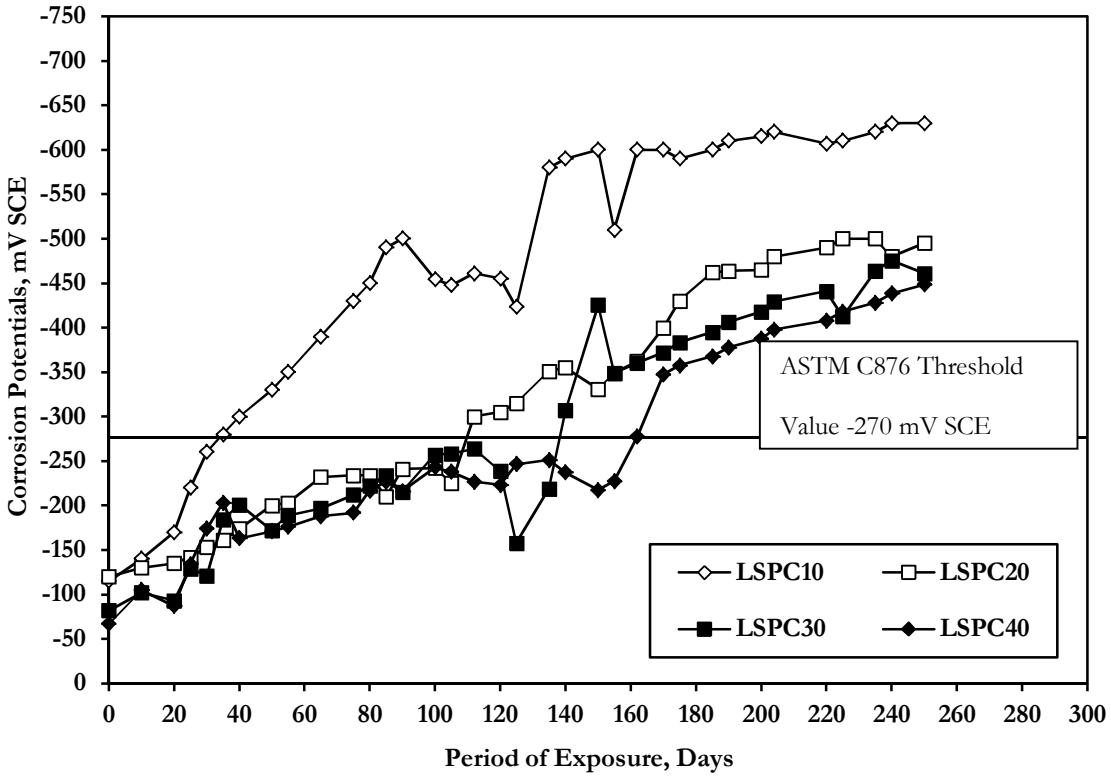


Figure 5. 21: Corrosion potentials on steel in LSPC SCC specimens exposed to 5% NaCl solution.

This could be as result of LSP providing the needed passivity around the reinforcement which reduces its corrosion. It could also be as result of reduction in the total porosity of the concrete which was made possible by the LSP in specimens.

SCC with Limestone Powder Addition to Cement

The variation of average corrosion potentials with the period of exposure to 5% NaCl solution are shown in Figure 5.21. From the Figure, there is a clear indication of an increase in corrosion potential as the percentages of the LSP replacing cement increases. It could be as result of increment in the total porosity of the concrete by the LSP in specimens.

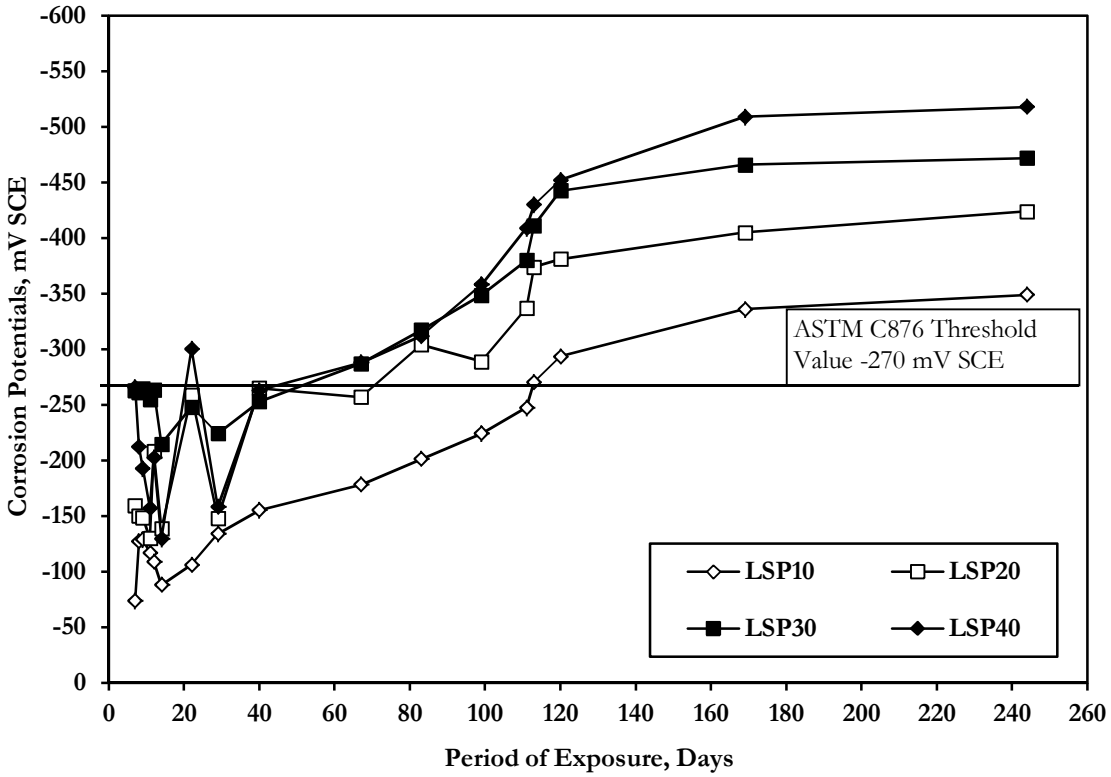


Figure 5. 22: Corrosion potentials on steel in LSP SCC specimens exposed to 5% NaCl solution.

SCC with Blend of Natural pozzolan and Limestone powder

The variation of average corrosion potentials with period of exposure to 5% NaCl solution are shown in Figure 5.22. From the Figure, there is a clear indication of an increase in corrosion potential from NP10/LSP10 to NP20/LSP10. The increase in the corrosion potential could be attributed to the increase in the NP in the blend. Active corrosion was indicated in the NP20/LSP10 species after about 15 days while it was noted after about 224 days in the NP10/LSP10 specimens.

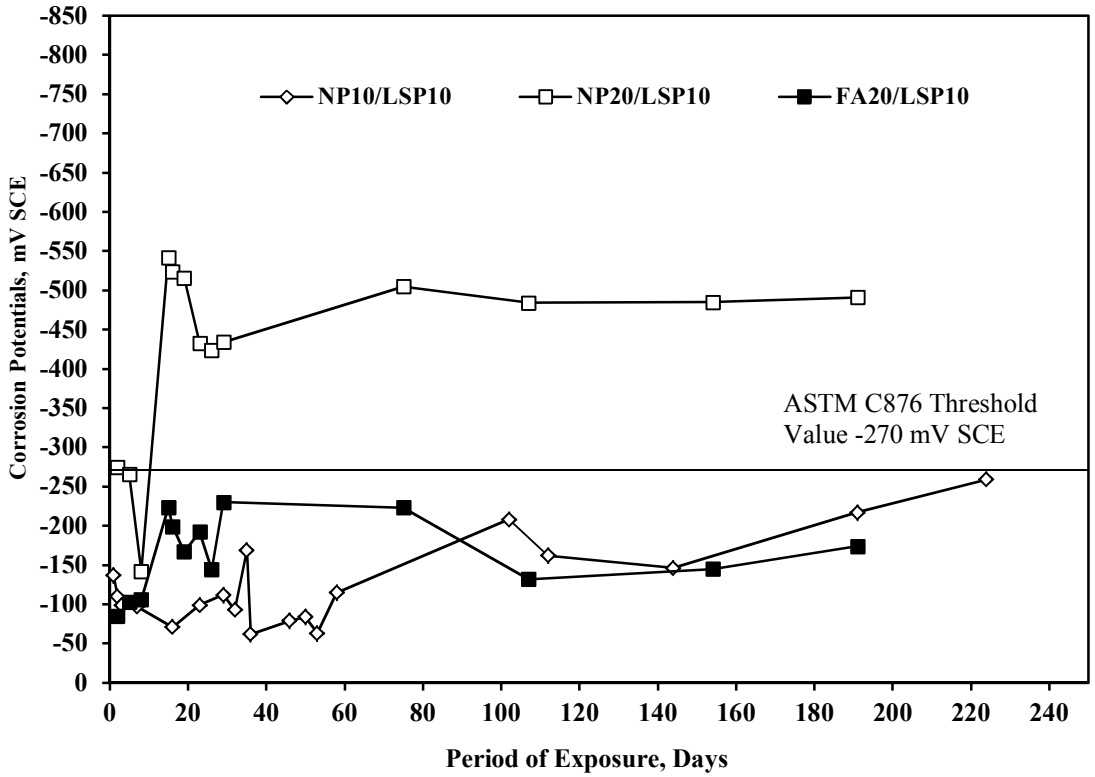


Figure 5. 23: Corrosion potentials on reinforcement bar in NP/LSP SCC specimens exposed to 5% NaCl solution.

5.5.2 Time to Initiation of Reinforcement Corrosion

Natural Pozzolan

The corrosion potentials vs. exposure time curves presented in Figure 5.19 were utilized to determine the time to initiation of reinforcement corrosion, based on the ASTM C 876 criterion. According to this criterion, there is more than 90% probability of reinforcement corrosion if the corrosion potential is more negative than –350 mv CSE; i.e., -270 mV SCE. The time to initiation of reinforcement corrosion is summarized in Table 5.4. The time to initiation of reinforcement corrosion was 84, 92, 106, 141 and 148 days,

respectively, in NP10, NP15, NP20, NP25 and NP30 specimens. This indicates that the corrosion resistance of concrete increases with increasing quantity of NP.

Table 5. 4: Time to initiation of reinforcement corrosion in NP specimens.

Mixture designation	Time to initiation of reinforcement corrosion, days
NP10	84
NP15	92
NP20	106
NP25	141
NP30	148

Limestone Powder Replacing Cement

The time to initiation of reinforcement corrosion was determined from the corrosion potentials vs. exposure time curves presented in Figure 5.20 based on the ASTM C 876 criterion. Table 5.5 shows the time to initiation of reinforcement corrosion. The time to initiation increases with an increase in the limestone replacement. As compared with the experimental result of Hassan et al [99] and Tsivilis et al [100], the trends of the data in Table 5.4 were identical.

Table 5. 5: Time to initiation of reinforcement corrosion for LSPC.

Mixture designation	Time to initiation of reinforcement corrosion, days
LSPC10	35
LSPC20	112
LSPC30	120
LSPC40	162

Limestone Powder Addition to Cement

The time to initiation of reinforcement corrosion was determined from the corrosion potentials vs. exposure time curves presented in Figure 5.21 based on the ASTM C 876 criterion. Table 5.6 shows the time of initiation of reinforcement corrosion. The time to initiation of corrosion decreased with an increase in the limestone addition to cement.

Table 5. 6: Time to initiation of reinforcement corrosion in LSP specimens.

Mixture designation	Time to initiation of reinforcement corrosion, days
LSP10	113
LSP20	83
LSP30	67
LSP40	22

Blend of Natural pozzolan and Limestone powder

The time to initiation of reinforcement corrosion was determined from the corrosion potentials vs. exposure time curves presented in Figure 5.22 based on the ASTM C 876 criterion. Table 5.7 shows the time of initiation of reinforcement corrosion. The time to initiation of corrosion decreased with an increase in the NP. Corrosion initiation was noted in the concrete species with a ternary blend of NP10/LSP10 and FA20/LSP10 while it initiated only after 15 days in the specie with a blend of NP20/LSP10.

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Table 5. 7: Time to initiation of reinforcement corrosion in NP/LSP specimens.

Mixture designation	Time to initiation of reinforcement corrosion, days
NP10/LSP10	Corrosion not initiated
NP20/LSP10	15
FA20/LSP10	Corrosion not initiated

5.5.3 Corrosion Current Density

Natural Pozzolan

The corrosion current density on reinforcing steel in NP specimens partially immersed in 5% NaCl solution is plotted against period of exposure in Figure 5.25. The corrosion current density increased with increasing period of exposure to the chloride solution. The maximum corrosion current density after close to one year of exposure is 0.41 $\mu A/cm^2$ from NP30. However, the corrosion current density was almost the same in all specimens.

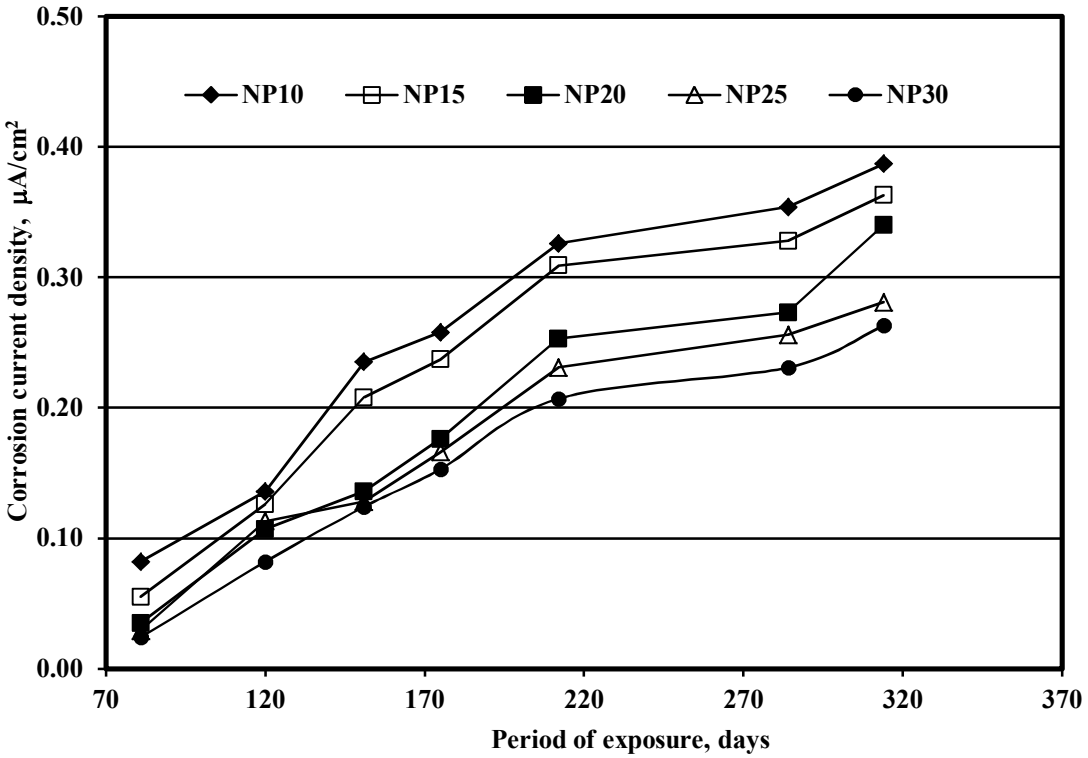

Figure 5. 24: Corrosion current density on steel in NP SCC specimens exposed to 5% NaCl solution.

Limestone Powder Replacing Cement

The corrosion current density on reinforcing steel in LSPC specimens partially immersed in 5% NaCl solution is plotted against period of exposure in Figure 5.26. The corrosion current density increased with the periods of exposure. The maximum corrosion current density after 194 days of exposure was 0.851 $\mu A/cm^2$ in the LSPC40 specimens. This -may be attributed to the high replacement of the cement which affected its microstructure through reduction in the C-S-H gel formed. This weakness in its microstructure decreases the resistivity of concrete that control the rate of reinforcement corrosion.

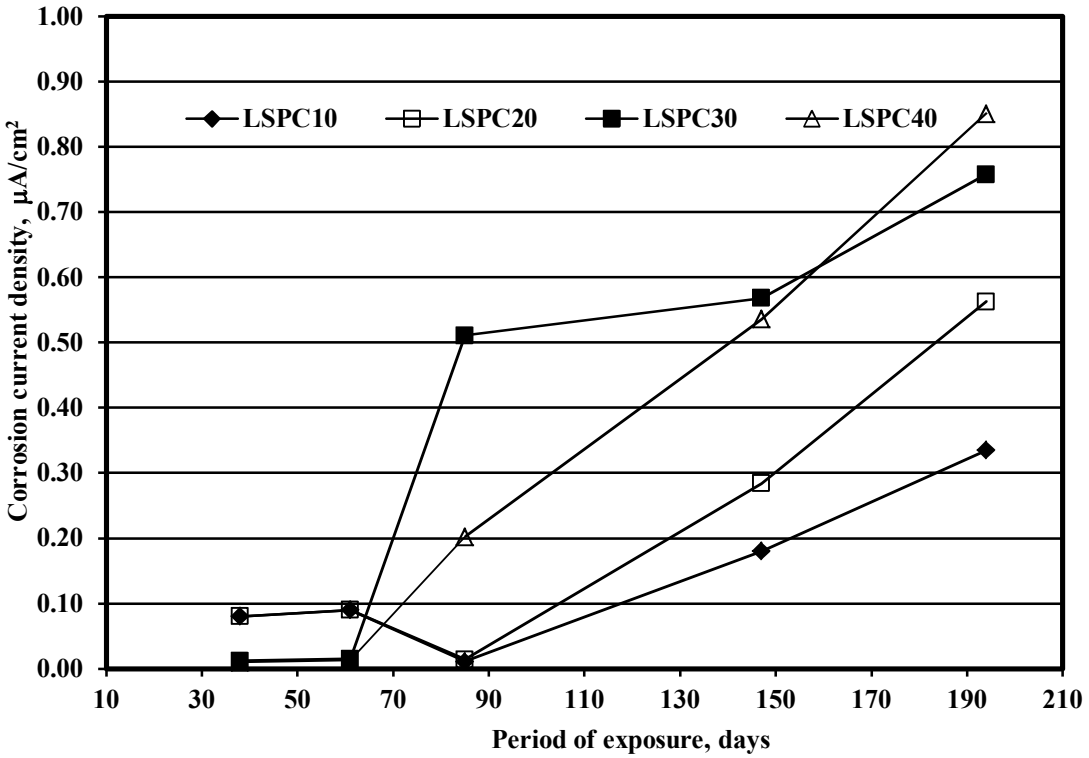

Figure 5. 25: Corrosion current density on steel in LSPC SCC specimens exposed to 5% NaCl solution.

Limestone Powder as Addition to Concrete

The corrosion current density on reinforcing steel in LSP SCC specimens immersed in 5% NaCl solution is plotted against period of exposure in Figure 5.27. The corrosion current density was very low with the periods of exposure. The maximum corrosion current density after 257 days of exposure was 0.037 $\mu A/cm^2$ from LSP40. This value of corrosion current density of the reinforcement bar reveals it is still in the passive state as pointed out in the works of Andrade et al [101]. The low value of its corrosion current density can be attributed to a very dense microstructure due to the addition of LSP where it acted more as filler.

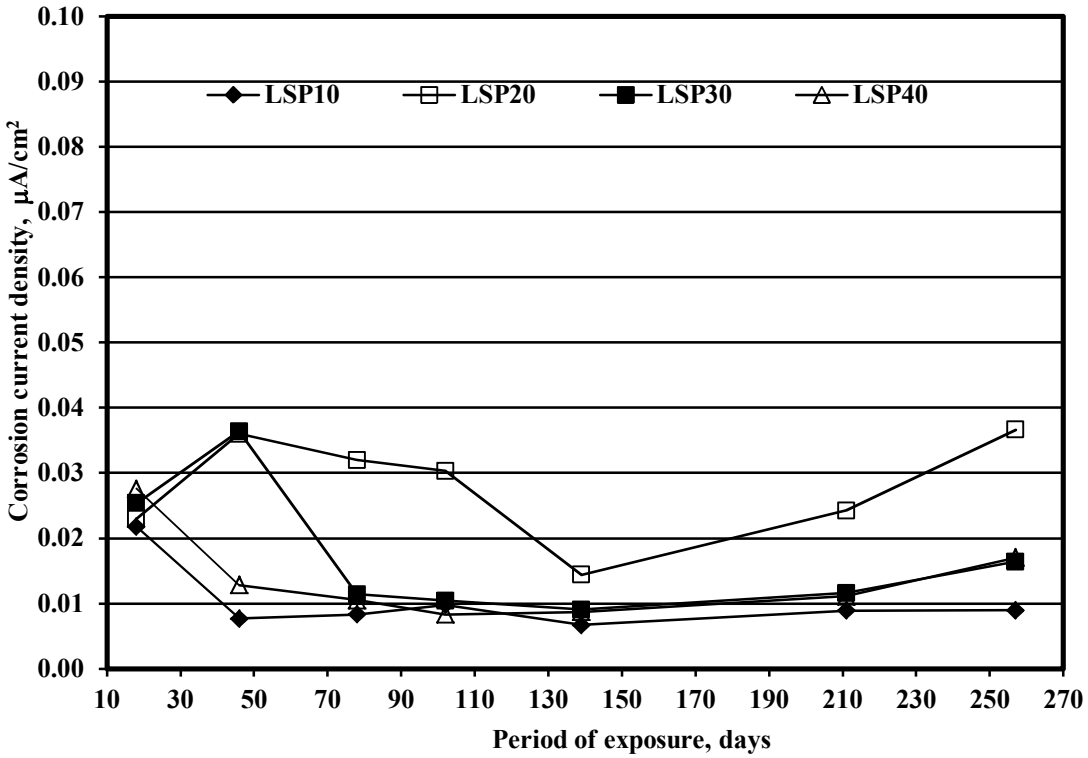

Figure 5. 26: Corrosion current density on steel in LSP SCC specimens exposed to 5% NaCl solution.

Blend of Natural pozzolan and Limestone powder

The corrosion current density on reinforcement bar in NP/LSP specimens immersed in 5% NaCl solution is plotted against period of exposure in Figure 5.8. The corrosion current density was very low throughout the stages of exposure except for NP20/LSP10 whose corrosion current density was high.

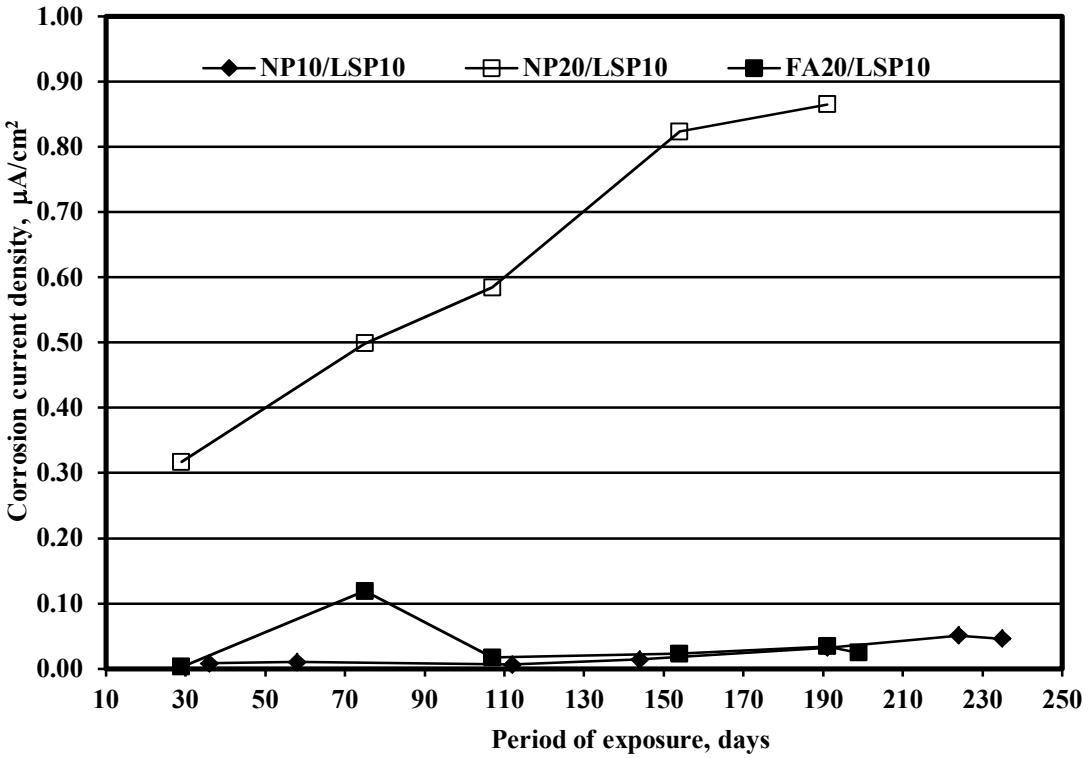

Figure 5. 27: Corrosion current density on reinforcement bar in NP/LSP SCC specimens exposed to 5% NaCl solution.

5.6 COST ANALYSIS

Despite its advantageous technical properties, the use of SCC by the precast and ready-mix industries is limited to special applications, due to the high material costs of additional ingredients, in particular, superplasticizers, stabilizers and additional cement. One alternative to reduce the cost of SCC is the incorporation of fillers like LSP and NP in high amount as used in this study. These are finely divided materials added to the concrete as separate ingredients during mixing. This high amount of substitution significantly improves the material cost effectiveness of the SCC, since the costs of these materials are not prohibitively high and most of the time, they are waste, ready to be disposed. In order to

compare the cost of the 15 investigated SCCs, the local unit costs of materials are collected and presented in Table 5.8 through 5.11. It should be noted that the overall cost of concrete production excludes the costs of transportation, handling, placement and quality control. From the table, it is seen that the cost of the control specimen which is without the mineral admixtures was more than mixes with the admixtures. This is to prove that there are savings in the costs and further money could be saved during the construction processes.

Table 5. 8: Cost Analysis for NP SCC mixtures.

Constituent	Rate, SR/ton (Lit)	NP 10		NP 15		NP 20		NP 25		NP 30	
		Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3
Cement, kg	350	405.00	141.75	382.50	133.88	360.00	126.00	337.50	118.13	315.00	110.25
Water, liter	0.15	205.41	30.81	205.72	30.86	206.04	30.91	206.36	30.95	206.67	31.00
Natural Pozzolan, kg	400	45.00	18.00	67.50	27.00	90.00	36.00	112.50	45.00	135.00	54.00
Fly ash, kg	600	-		-		-		-		-	
Coarse aggregate, kg	75	907.80	68.09	919.10	68.93	930.40	69.78	941.70	70.63	953.00	71.48
Fine aggregate, kg	40	907.80	36.31	919.10	36.76	930.40	37.22	941.70	37.67	953.00	38.12
Lime stone powder, kg	50	-	-	-	-	-	-	-	-	-	-
Glenium 51, *l*	11	1.6	17.60	1.6	17.60	1.6	17.60	1.6	17.60	1.6	17.60
Stream 2, *l*	10	0..5	5.00	0..5	5.00	0..5	5.00	0..5	5.00	0..5	5.00
TOTAL (SR)			317.56		320.03		322.51		324.98		327.45

Table 5. 9: Cost Analysis for LSP SCC mixtures.

Constituent	Rate, SR/ton (Lit)	LSP 10		LSP 20		LSP 30		LSP 40	
		Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3
Cement, kg	350	450.00	157.50	450.00	157.50	450.00	157.50	450.00	157.50
Water, liter	0.15	199.55	29.93	195.09	29.26	195.08	29.26	194.21	29.13
Natural Pozzolan, kg	400	-	-	-	-	-	-	-	-
Fly ash, kg	600	-	-	-	-	-	-	-	-
Coarse aggregate, kg	75	651.95	48.90	453.01	33.98	281.32	21.10	131.64	9.873
Fine aggregate, kg	40	814.94	32.60	755.01	30.20	703.30	28.13	658.21	26.33
Lime stone powder, kg	50	162.93	8.15	302.02	15.10	421.98	21.10	526.57	26.33
Glenium 51, *l*	11	1.6	17.60	1.6	17.60	1.6	17.60	1.6	17.60
Stream 2, *l*	10	0..5	5.00	0..5	5.00	0..5	5.00	0..5	5.00
TOTAL (SR)			299.68		288.64		279.69		271.70

Table 5. 10: Cost Analysis for LSPC SCC mixtures.

Constituent	Rate, SR/ton (Lit)	LSP 10C		LSP 20C		LSP 30C		LSP 40C	
		Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3
Cement, kg	350	405.00	141.45	360.00	126.00	315.00	110.25	270.00	94.50
Water, liter	0.15	204.26	30.64	203.57	30.54	202.88	30.43	202.20	30.33
Natural Pozzolan, kg	400	-	-	-	-	-	-	-	-
Fly ash, kg	600	-	-	-	-	-	-	-	-
Coarse aggregate, kg	75	865.05	64.88	841.44	63.11	817.82	61.34	794.20	59.57
Fine aggregate, kg	40	865.05	34.60	841.44	33.66	817.82	32.71	794.20	31.77
Lime stone powder, kg	50	45.00	2.25	90.00	4.50	135.00	6.75	180.00	9.00
Glenium 51, *l*	11	1.6	17.60	1.6	17.60	1.6	17.60	1.6	17.60
Stream 2, *l*	10	0..5	5.00	0..5	5.00	0..5	5.00	0..5	5.00
TOTAL (SR)			296.42		280.41		264.08		247.77

Table 5. 11: Cost Analysis for blend of NP and LSP SCC mixtures.

Constituent	Rate, SR/ton (Lit)	NP 10/LSP 10		NP 20/LSP 10		FA 20/LSP 10	
		Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3	Quantity	Cost, SR/m^3
Cement, kg	350	405.00	141.75	405.00	141.75	405.00	141.75
Water, liter	0.15	199.55	29.93	195.09	29.26	195.09	29.26
Natural Pozzolan, kg	400	162.99	65.20	302.01	120.84	-	-
Fly ash, kg	600	-	-	-	-	302.01	181.206
Coarse aggregate, kg	75	651.96	48.90	453.01	33.98	453.01	33.98
Fine aggregate, kg	40	814.95	32.60	755.02	30.20	755.02	30.20
Lime stone powder, kg	50	45.00	2.25	45.00	2.25	45.00	2.25
Glenium 51, *l*	11	1.6	17.60	1.6	17.60	1.6	17.60
Stream 2, *l*	10	0..5	5.00	0..5	5.00	0..5	5.00
TOTAL (SR)			343.23		380.88		441.25

5.7 GENERAL DISCUSSION

The data developed in this investigation have shown that the addition of LSP and NP to cement and its replacement by LSP improves the properties of SCC. The SCC specimens met all the flowability requirements and the mechanical and the durability characteristics of the developed SCC mixtures proved excellent except for a few.

In the fresh state, mixes with w/c = 0.4, cement content = 450kg/m^3 prepared with NP and LSP have positively influenced both the stability of SCC and its resistance to segregation. It has been verified, by using the slump flow, V-funnel and U-tube tests that SCC developed with NP and LSP, also achieved consistency and self-compactability under its own weight, without any external vibration or compaction.

SCC can be obtained in such a way, by adding local materials, NP and LSP, so that its compressive strengths is higher than those of conventional vibrated concrete and better durability properties.

For NP SCC specimens, the compressive strength increase with time of curing. The maximum compressive strength was found with SCC specimen with 20 % replacement of cement (NP20) which by typical classification, could be called high strength concrete. Other NP SCC specimens also have compressive strengths way higher than those of CVC because they show compact and dense structure. For the durability properties, satisfactory performances were recorded with the NP SCC specimens especially in the corrosion studies which are pertinent to this region. This concrete could be used conveniently where special properties like high strength and satisfactory durability behavior is important and highly desired.

For LSP SCC specimens, the compressive strength is higher than those reported for NP SCC specimen and had better durability properties also, except for the LSP30 and

LSP40 that had high chloride permeability. The maximum compressive strength was found with 10 % addition to cement and high enough to be called high strength concrete. All the LSP SCC specimens have high compressive strength and only two SCC specimens, LSP10 and LSP20, performed satisfactory in the durability tests. For applications where strength is the most important, all LSP SCC specimens would be perform excellently but applications where strength and durability requirements are paramount, LSP10 and LSP20 would be the only recommended.

For LSPC SCC specimens, the compressive strength was less than those of LSP SCC specimens but higher than those of the CVC. The compressive strengths qualify the specimens for normal strength concretes. For durability properties, the specimens behaved fairly in response to chloride permeability and sulfates attack which limits their applications to areas where chloride and sulfates are not prone. LSP 20C, LSP30C and LSP40C could all be used in areas where the chloride and sulfate concentration are not severe.

For the SCC blend of NP and LSP specimens, the compressive strength of these specimens are high enough for a typical high strength concrete. The mechanical and durability properties of these specimens were satisfactory except for NP20/LSP10 that performed below expectation in the corrosion studies.

The summary of the mechanical and durability tests results are shown Table 5.12 below. These results are of great importance for regions where supplementary cementing materials are not available locally and have to be imported from other regions but the good news is it is locally available in Saudi Arabia. Since high quantity of cementitious materials is used in SCC, incorporation of limestone and natural pozzolan, as an addition and a replacement of therefore, decreases the overall cost of SCC. Also, the use of

limestone powder and natural pozzolan as a partial replacement of cement will lead to a reduction in the greenhouse gas emission.

Table 5. 12: Summary of tests results for SCC specimens

TESTS	MIXTURES															
	NP10	**NP15**	**NP20**	**NP25**	**NP30**	**LSP10**	**LSP20**	**LSP30**	**LSP40**	**LSP10C**	**LSP20C**	**LSP30C**	**LSP40C**	**NP10/LSP10**	**NP20/LSP10**	**FA20/LSP10**
28-day compressive stength	51.94	47.32	44.65	44.20	44.16	78.21	68.34	67.88	67.33	56.81	45.67	46.02	35.18	61.86	60.51	60.96
90-day compressive stength	56.72	60.88	61.41	59.19	57.98	80.42	71	70.25	67.56	62.86	50.19	49.35	40.52	75.5	67.91	69.13
Drying Shrinkage strain	885	893	945	970	993	596	643	662	725	686.89	652.78	661.03	704.55	609.768	643.358	714.527
Corrosion current density	0.387	0.363	0.34	0.281	0.263	0.022	0.023	0.025	0.028	0.335	0.563	0.758	0.851	0.051	0.86514	0.119
Corrosion potential @ initiation	-430	-393	-370	-391	-354	-270	-304	-287	-300	-280	-300	-307	-278	-259	-491	-174
Time to initiation of corrosion	84	92	106	141	148	113	83	67	22	35	112	120	162	0	15	0
Chloride permeability	Mod	Mod	Mod	Mod	Mod	Mod	Mod	High	High	High	High	High	High	Mod	Mod	Mod
Sulfate Resistance (3-month Strength Loss)	55.13	51.63	50.71	40.93	39.06	63.93	73.28	71.01	69.4	52.77	45.1	42.56	31.93	63.87	47.39	52.06
Sulfate Resistance (6-month Strength Loss)	41.77	46.34	44.82	41.53	41.62	56.68	57.74	53.18	44.22	42.69	17.44	35.43	28.37	47.56	40.27	52.7

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Based on the data developed in this study, the following conclusions can be drawn:

6.1.1 Natural Pozzolan

1. Natural pozzolan (NP), one of the locally available materials can be used for producing SCC. It has been verified using the slump flow, V-funnel and U-tube tests where it achieved consistency and self-compactability under its own weight, without any external vibration or compaction. It also influenced the stability and segregation resistance of the developed SCC.
2. NP SCC exhibited acceptable mechanical and durability properties. After 28 days of water curing, the compressive strength of 10-30 % NP SCC was in the range of 44 to 52 MPa. The compressive strength decreased with an increase in the quantity of NP and 20% NP cement concrete proved to the best. The use of about 30% NP in SCC is beneficial as it not only reduces the cost but enhancement in the durability.
3. The chloride permeability of all SCC specimens prepared using NP was 'moderate' according to ASTM C 1202 criteria.
4. The compressive strength of NP SCC specimens decreased on exposure to sulfate solution except for NP20 SCC specimen that maintained its increment in strength, although it was minimal.

5. The maximum shrinkage was noted in the SCC specimen with the highest percentage of NP and the minimum shrinkage was measured in with the specimen with the lowest percentage of NP.
6. The corrosion potentials on steel in NP cement concrete specimens with high quantity of NP were lower than the SCC specimens with low quantity of the same material.
7. After 200 days of exposure to NaCl solution, the maximum corrosion current density of embedded steel in the NP SCC specimens was 0.41$\mu A/cm^2$, a low value maintained throughout the stages of exposure.

6.1.2 Limestone Powder

1. Limestone powder (LSP), one of the locally available materials can be used for producing SCC. It has been verified using the slump flow, V-funnel and U-tube tests where it achieved consistency and self-compactability under its own weight, without any external vibration or compaction. It also influenced the stability and segregation resistance of the developed SCC.
2. The compressive strength of LSP SCC specimens was more than that of NP SCC specimens. The highest recorded compressive strength (78 MPa) at 28 days was measured in the SCC with 10% LSP (used as addition) and the least (67 MPa) was recorded with the highest LSP addition (40%). The compressive strength of SCC with cement replacement by LSP was less than that in the SCC in which LSP was used as an addition (aggregates were replaced). The highest compressive strength of 57 MPa at 28 days of water curing was measured in SCC with 10 % LSP replacement

of cement, while the least strength of 35MPa was noted at in the specimens with 40 % LSP used as a replacement of cement.

3. The chloride permeability of specimens with 10 and 20% LSP was moderate but as the LSP increased, the chloride permeability also increased. Also, the chloride permeability of concrete specimens' replacement with LSP, the permeability was high.
4. The compressive strength of LSP SCC specimens decreased on exposure to sulfate solution for the entire SCC specimens but was within the acceptable limits.
5. The shrinkage strain of SCC with LSP, both replacement and addition, increased with an increase in the quantity of LSP. The drying shrinkage strain in the NP SCC was more than that in LSP SCC.
6. The corrosion potentials on steel in SCC with LSP replacing aggregate were lower than those in the SCC specimens with low quantity of the same material. Reverse is the situation with in the SCC specimens in which cement was replaced with LSP.
7. After 200 days of exposure, the maximum corrosion current density on steel in the LSP and LSPC SCC specimens was 0.037 and 0.851$\mu A/cm^2$ respectively, making the LSPC i.e. LSP replacing cement the most susceptible to chloride attack.

6.1.3 Blend of Natural Pozzolan and Limestone Powder

1. The compressive strength of SCC with a blend of NP and LSP is high with NP10/LSP10 giving the highest early and later age strength followed by FA20/LSP10 and then NP20/LSP10.
2. The chloride permeability of all SCC specimens prepared using a blend of NP and LSP was 'moderate' according to ASTM C 1202 criteria. The NP20/LSP10

compared favorably well with the SCC prepared with 20 % FA plus 10 % LSP FA20/LSP10.

3. After six months of exposure to the sulfate solution, the rate of strength loss in NP20/LSP10 SCC specimen is higher than that in the NP10/LSP10 SCC specimen. The performance of FA20/LSP10 SCC was favorable with an increase in the compressive strength.
4. For the ternary mixtures, the shrinkage strain in NP20/LSP10 specimen was more than that of NP10/LSP10. The control mixture gave a higher shrinkage strain of the control mixture was more than that of the developed mixtures.
5. There is a clear indication of an increase in the corrosion potential from NP10/LSP10 to NP20/LSP10, making the former preferred over the latter.
6. After 200 days of exposure, the corrosion current density on steel in the NP and LSP blends was low throughout the stages of exposure except for NP20/LSP10 whose corrosion current density was on a high side.

Finally, this high amount of substitution significantly improves the material cost effectiveness of the SCC and also the cost of developed SCC with LSP is less than that of the SCC with NP. And consequently a significant reduction in the consumption of cements which by extension leads to a reduction in the greenhouse gases.

6.2 RECOMMENDATIONS

The results of this study have indicated that SCC mixes with LSP or NP meet the flow requirements and exhibit good mechanical properties and durability characteristics. The better durability of NP and some LSP mixtures, particularly against reinforcement corrosion,

means enhanced service life of structures prepared with these materials. The reduction in the initial cost and increased durability results in a significant cost savings. As such, SCC with NP (10-30%), LSP (10-20%) and NP10/LSP10 are recommended. For guidance on the applicability of the developed SCC with the two materials used – NP and LSP based on cost and required durability and mechanical properties, Table 6.1 below may be used.

Table 6. 1 Applicability of developed SCC.

CONCRETE	**COST/m^3 (SAR)**	**APPLICABILITY**
Limestone powder replacing coarse aggregate (LSP)	LSP10(300), LSP20(289)	High strength (> 65 MPa) structural concrete with medium durability requirements
Limestone powder replacing cement (LSPC)	LSP10C(296), LSP20C(280)	Low to Medium strength (35 - 57 MPa) structural concrete with low durability requirements
Natural pozzolan replacing cement (NP)	NP10(318), NP15(320), NP20(322), NP25(324), NP30(327)	Medium strength (50 – 60 MPa) structural concrete with high durability requirements
Blend of Natural pozzolan and Limestone powder (NP/LSP)	NP10/LSP10(343)	High strength (>60 MPa) structural concrete with medium durability

		requirements

It is also recommended for future work the experimental investigations be carried out on other local materials, such as bag house dust (BHD), cement kiln dust (CKD), metakaolin (MK), pulverized steel slag (PSS), etc., to study their effect on the mechanical properties and durability characteristics of SCC.

REFERENCES

1. Khayat, K.H., Assaad, J., and Daczko, J., *Comparison of Field-oriented Test Methods to Assess Dynamic Stability of Self-Consolidated Concrete.* ACI Materials Journal, 2004. **101**(2): p. 168-176.
2. Bouzoubaâ, N., and Lachemi, M., *Self-compacting concrete incorporating high volumes of class F fly ash: Preliminary results. Cement and Concrete Research*, 2001. **31**(3): p. 413-420.
3. Okamura, H., and Ouchi, M. *Self-compacting concrete-development, present and future*. in *Proceedings of the First International RILEM symposium on Self-Compacting Concrete*. 1999.
4. Okamura, H., and Ouchi, M., *Self-compacting concrete.* Journal of Advanced Concrete Technology, 2003. **1**(1): p. 5-15.
5. Mata, L.A., *Implementation of Self-Consolidating Concrete (SCC) for Prestressed Concrete Girders*. 2004, North Carolina State University.
6. Siddiqui, N., *Influence of Fluidity on Reliability of SCC Produced Using Local Saudi Materials.* Arabian Journal for Science and Engineering, 2011. **36**(2): p. 203-214.
7. Su, N., Hsu, Kung-Chung., Chai, His-Wen, *A simple mix design method for self-compacting concrete.* Cement and Concrete Research, 2001. **31**(12): p. 1799-1807.
8. Kapoor, Y.P., Munn, C., and Charif, K.„ *Self-Compacting Concrete-An Economic Approach*, in *7th International Conference on Concrete in Hot & Aggressive Environments*. 2003: Manama, Kingdom of Bahrain. p. 509-520.
9. Ouchi, M., Nakamura, S., Osterson, T., Hallberg, S., and Lwin, M., , *Applications of Self-Compacting Concrete in Japan, Europe and the United States.* ISHPC, 2003: p. 1-20.
10. AbdulHameed, M., *A study of mix design and durability of self compacting concrete.* M.S. Thesis, King Fahd University of Petroleum and Minerals, 2005.
11. Ozyildirim, C., and Lane, D.S., , *Final report on evaluation of selfconsolidating concrete.* Virginia Transportation Research Council, VTRC 03-R13, 2003: p. 1-15.
12. Khayat, K.H., Paultre, P., and Tremblay, S.„ *Structural Performance and In-Place Properties of Self Consolidating Concrete Used for Casting Highly Reinforced Columns.* ACI Materials Journal, 2001. **98**(5): p. 371-378.
13. Chan, Y.W., Chen, Y. S., and Liu, Y. S.„ *Development of Bond Strength of Reinforcement Steel in Self- Consolidating Concrete.* ACI Materials Journal, 2003. **100**(4): p. 490-498.
14. Sonebi, M., Tamini, A., and Bartos, P. J. M., *Performance and Cracking Behavior of Reinforced Beams Cast with Self-Consolidating Concrete.* ACI Materials Journal, 2003. **100**(6): p. 492-500.
15. Khayat, K.H., and Assaad, J., *Air-void Stability in Self-Consolidating Concrete.* ACI Materials Journal, 2002. **99**(4): p. 408-416.
16. Dehn, F., Holschemacher, K., and Weibe, D., , *Self-Compacting Concrete Time Development of the Material Properties and the Bond Behavior.* LACER, 2000(5): p. 115-124.
17. Okamura, H., and Ozawa, K., *hMix design for self-compacting concrete.* Concrete Library of JSCE, 1995. **25**: p. 107-120.

18. EFNARC, *Specification and Guidelines for Self-Compacting Concrete*. EFNARC, UK (www.efnarc.org), 2002: p. 1-32.
19. BIBM, C., EFCA, EFNARC, and ERMCO, , *The European Guidelines for Self-Compacting Concrete: Specification, Production and Use*. 2005.
20. Bui, V.K., Montgomery, D., Hinczak, I., and Turner, K., , *Rapid testing method for segregation resistance of self-compacting concrete*. Cement and Concrete Research,, 2002. **32**: p. 1489-1496.
21. Zhu, W., Gibbs, C J., and Bartos, P J M., , *Uniformity of in situ properties of self compacting concrete in full-scale structural elements*. Cement & Concrete Composites, 2001. **23**: p. 57-64.
22. Khayat, K.H., Manai, k., and Trudel, A.,, *In situ mechanical properties of wall element cast using self consolidating concrete*. ACI. Materials journal 1997. **94**(6): p. 491-500.
23. Sonebi, M., *Medium strength self-compacting concrete containing fly ash: modeling using factorial experimental plans*. Cement and Concrete Research, 2004b. **34**: p. 1199-1208.
24. Uzal, B., and Turanli, L., , *Studies on Blended Cements Containing a High Volume of Natural Pozzolans*. Cement and Concrete Research, 2003. **33**(11): p. 1777-1781.
25. Ramsburg, P., and Neal, R.E., , *The use of a natural pozzolan to enhance the properties of self-consolidating concrete*. (www.oldcastle-precast.com), , 2003: p. 1-7.
26. Malhorta, V.M., *Supplementary Cementing Materials*. CANMET Special Publication SP 86-8E, Energy, Mines and Resources Ottawa, Canada,, 1987: p. 25.
27. Ramachandran, V.S., *Concrete admixtures handbook: properties, science, and technology*. 1995: Noyes Publications.
28. Habert, G., Choupay, N., Montel, J.M., Guillaume, D., and Escadeillas, G., *Effects of the secondary minerals of the natural pozzolans on their pozzolanic activity*. Cement and Concrete Research; , 2008. **38**(7): p. 963-975.
29. Kogel, J.E., et al., *Industrial minerals & rocks: commodities, markets, and uses*. 2006: Society for Mining, Metallurgy, and Exploration.
30. Atlas of Industrial Minerals, *"Pozzolan and Basalt"*., Ministry of Petroleum and Mineral Resources, Editor, Directorate General of Mineral Resources, Kingdom of Saudi Arabia.
31. Information Bulletin No. 13, Ministry of Petroleum and Mineral Resources, Editor. 1419H (1998): Directorate General of Mineral Resources, Kingdom of Saudi Arabia.
32. Domone, P.L., *A review of the hardened mechanical properties of self-compacting concrete*. Cement and Concrete Composites, 2007. **29**(1): p. 1-12.
33. Billberg, P. *Fine mortar rheology in mix design of SCC,* . in *Proceedings of First International RILEM Symposium on Self-Compacting Concrete*. 1999. RILEM Publications, S.A.R.L., Stockholm, .
34. Nishibayashi, S., Yoshino, A., and Inoue, S.,, *Effect of properties of mix constituents on rheological constant of SCC , Production Methods and Workability of Concrete,* . E & FN Spon, London, 1996: p. pp. 255– 262.

35. Zhu, W. and J.C. Gibbs, *Use of different limestone and chalk powders in self-compacting concrete.* Cement and Concrete Research, 2005. **35**(8): p. 1457-1462.
36. Bosiljkov, V.B., *SCC mixes with poorly graded aggregate and high volume of limestone filler.* Cement and Concrete Research, 2003. **33**(9): p. 1279-1286.
37. Naik, T.R., Kraus, R.N., Chun, Y., Canpolat, F., and Ramme, B.W., , *Use of limestone quarry by-products for developing economical self compacting concrete*, in *CANMET/ACI Three-Day International Symposium on Sustainable Development of Cement and Concrete,*. 2005, Center for By-Products Utilization, Report No. CBU-2005-14, REP-585.: Toronto, CANADA.
38. Ho, D.W.S., Sheinn, A. M. M., Ng, C. C., and Tam, C. T., *The use of quarry dust for SCC applications.* Cement and Concrete Research, 2002. **32**(4): p. 505-511.
39. Ho, D.W.S., et al., *The use of quarry dust for SCC applications.* Cement and Concrete Research, 2002. **32**(4): p. 505-511.
40. Su, J.K., Cho, S.W., Yang, C.C., and Huang, R.,, *Effect of sand ratio on the elastic modulus of self-compacting concrete.* Journal of Marine Science and Technology, 2002. **10**(1): p. 8-13.
41. Gerwick, B.C.J., *Construction of Prestressed Concrete Structures,*, ed. Second Edition. 1993: John Wiley and Sons Inc., .
42. Ouchi, M., Hibino, M., Sugamata, T., and Okamura, H., , *A quantitative evaluation method for the effect of superplasticizer in self-compacting concrete.* Transactions of JCI, 2001: p. pp. 15-20.
43. Lachemi, M., Hossain, K. M. A.,Lambros, V.,Nkinamubanzi, P. C., and Bouzoubaâ, N., *Performance of new viscosity modifying admixtures in enhancing the rheological properties of cement paste.* Cement and Concrete Research, 2004. **34**(2): p. 185-193.
44. Munn, C., *Self Compacting Concrete (SCC): Admixtures, Mix Design Consideration and Testing of Concrete.* A Technical Paper Presented in the Meeting of the ACI, Saudi Arabia Chapter, Eastern Province. , 2003.
45. Patel, R., Hossain, K.M.A., Shehata, M., Bouzoubaa, N., and Lachemi, M., , *Development of statistical models for mixture design of high-volume fly ash self-consolidating concrete.* ACI Materials Journal,, 2004. **101**(4): p. 294-302.
46. Sonebi, M., *Applications of statistical models in proportioning medium strength self consolidating concrete.* ACI Materials Journal, , 2004a. **101**(5): p. 339-346.
47. Nagamoto, N., and Ozawa, K., , *Mixture proportions of self-compacting high performance concrete.* ACI International,, 1997(SP-172): p. 623-636.
48. Xie, Y., Liu, B., Yin, J., and Zhou, S.,, *Optimum Mix Parameters of High-Strength Self-Compacting Concrete with Ultrapulverized Fly Ash.* Cement and Concrete Research, 2002. **32**: p. 477-480.
49. Brameshuber, W., and Uebachs, S.,, *Self-Compacting Concrete – Application in Germany*, in *6th International Symposium on High Strength/High Performance Concrete,*. 2002: Leipzig,. p. 1503-1514.

50. Nehdi, M., Pardhan, M., and Koshowski, S., , *Durability of self- consolidating concrete incorporating high-volume replacement composite cements*. Journal of Cement and Concrete Research, 2004. **34**: p. 2103-2112.
51. Kumar, P., Haq, M., Ajazul, and Kaushik, S.K. , *Early age strength of SCC with large volumes of fly ash,*. Indian Concrete Journal,, 2004. **Vol. 78,**(No. 6,): p. p 25-29.
52. Holschemacher, K., and Klug, Y.,, *Database for the Evaluation of Hardened Properties of SCC*. 2002: p. 123-134.
53. Leemann, A., and Hoffmann, C.,, *Properties of self compacting and conventional concrete-differences and similarities*, in *Magazine of Concrete Research,*. 2005. p. 315-319.
54. Guidelines on SCC (Task 9), *Brite EuRam Contract No. BRPR-CT96-0366,*. 2000(Rev. no.: 10,): p. pp. 2-48.
55. Plante, P., and Bilodeau, A.,, *Rapid Chloride Permeability Test: Data on Concrete Incorporating Supplementary Cementing Materials, Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, V. M. Malhotra, ed.,* . American Concrete Institute Trondheim, Norway., 1989: p. 626-644.
56. ASTM C1202., *Standard test method for Electrical Indication of Concrete's ability to Resist Chloride Ion Penetration*, in *Annual Book of ASTM Standards, Vol. 4.02,*. 1994, American Society for Testing and Materials,: Philadelphia.
57. Persson, B., and Terrasi, G.P.,, *High performance self compacting concrete, HPSCC*, in *6th International Symposium on High Strength/High Performance Concrete*. 2002: Leipzig. p. 1273-1290.
58. Persson, B., *A comparison between mechanical properties of selfcompacting concrete and the corresponding properties of normal concrete*. Cement and Concrete Research., 2001. **31**: p. 193-198.
59. Corinaldesi, V., and Moriconi, G., *Durable fiber reinforced self-compacting concrete*. Cement and Concrete Research, 2004. **34**(2): p. 249-254.
60. Persson, B., *Sulphate resistance of self-compacting concrete*. Cement and Concrete Research, 2003. **33**(12): p. 1933-1938.
61. Uysal, M. and M. Sumer, *Performance of self-compacting concrete containing different mineral admixtures*. Construction and Building Materials, 2011. **In Press, Corrected Proof**.
62. Shamsad A, Abul Kalam Azad, and Mohammed Abdul Hameed, *A Study of Self-Compacting Concrete Using Local Marginal Aggregates*. The Arabian Journal for Science and Engineering, 2008. **33**(2B): p. 437-442.
63. Stern, M.a.G., A.L, *Electrochemical polarization. No. 1. Theoretical analysis of the shape of polarization curves*. Journal of Electrochemical. Society, 1957. **104**(1): p. 56.
64. Andrade, C., Castelo, V., Alonso, C. and Gonzalez, J.A., *Determination of the Corrosion Rate of Steel Embedded in Concrete*. ASTM Special Technical Publication STP 906,Philadelphia, 1986: p. 43.
65. Lambert, P., Page, C.L., and Vassie, P.R.W, *Investigations of Reinforcement Corrosion. Electrochemical Monitoring of Steel in Chloride-contaminated Concrete*. Materials and Structures, 1991. **24**: p. 351-358.

66. Targan, S., et al., *Influence of natural pozzolan, colemanite ore waste, bottom ash, and fly ash on the properties of Portland cement.* Cement and Concrete Research, 2003. **33**(8): p. 1175-1182.
67. Shannag, M.J., *High strength concrete containing natural pozzolan and silica fume.* Cement and Concrete Composites, 2000. **22**(6): p. 399-406.
68. Shannag, M.J. and A. Yeginobali, *Properties of pastes, mortars and concretes containing natural pozzolan.* Cement and Concrete Research, 1995. **25**(3): p. 647-657.
69. Yetgin, S. and A. Cavdar, *Study of Effects of Natural Pozzolan on Properties of Cement Mortars.* ASCE Journal of Materials in Civil Engineering, 2006. **18**(6): p. 813.
70. Mehta, P.K., *Studies on blended Portland cements containing Santorin earth.* Cement and Concrete Research, 1981. **11**(4): p. 507-518.
71. Turanli, L., B. Uzal, and F. Bektas, *Effect of large amounts of natural pozzolan addition on properties of blended cements.* Cement and Concrete Research, 2005. **35**(6): p. 1106-1111.
72. Bonavetti, V., et al., *Influence of initial curing on the properties of concrete containing limestone blended cement.* Cement and Concrete Research, 2000. **30**(5): p. 703-708.
73. Péra, J., S. Husson, and B. Guilhot, *Influence of finely ground limestone on cement hydration.* Cement and Concrete Composites, 1999. **21**(2): p. 99-105.
74. Ingram, K. and K. Daugherty. *Limestone additions portland cement: uptake, chemistry and effects.* in *Proc. 9th Int. Congr. Chem. Cem.* 1992. New Delhi, India: National Council for Cement and Building Materials.
75. Billberg, P. in *Proceedings of the Second International Symposium on Self-compacting Concrete.* Influence of filler characteristics on SCC rheology and early hydration.
76. Sharma R.L and Pandey S.P., *Influence of mineral additives on the hydration characteristics of ordinary Portland cement.* Cement & Concrete Research, 1999. **29**: p. 1525-1529.
77. Sari M., Prat E., and Labastire J.F., *High strength self compacting concrete - Original solutions associating organic and inorganic admixtures,.* Cement & Concrete Research, 1999. **29**: p. 813-818.
78. Kadri E.H., Aggoun S., and Duval R. *Influence of grading and diameter size of admixture on the mechanical properties of cement mortars.* in *Proceedings of the international Symposium on Non-Traditional cement and concrete*. June, 2002. Brno.
79. Kadri E.H. and Duval R., *Effect of ultrafine particles on heat of hydration of cement mortars.* ACI Materials Journal, March-April, 2002.
80. Bentz, D.P., *Modeling the influence of limestone filler on cement hydration using CEMHYD3D.* Cement and Concrete Composites, 2006. **28**(2): p. 124-129.
81. Anne-Mieke Poppe and Geert De Schutter. *Effect of Limestone Filler on the Cement Hydration in Self-Compacting Concrete.* 17-20 August, 2003. 3rd International Symposium on Self-Compacting Concrete.
82. Erdogan T.Y., *Admixtures for concrete, first ed.,.* 1997, The Middle East Technical University Press, Ankara.
83. Gurol G., *ooComponents for Economic Concrete, cement/water/fine and coarse aggregate/chemical and mineral admixtures.* Journal of Des. Construction, 1999. **164**: p. 66-74 (InTurkish).

84. Gastaldini, A.L.G., et al., *Chloride penetration and carbonation in concrete with rice husk ash and chemical activators*. Cement and Concrete Composites, 2007. **29**(3): p. 176-180.
85. Chindaprasirt, P., et al., *Influence of fly ash fineness on the chloride penetration of concrete*. Construction and Building Materials, 2007. **21**(2): p. 356-361.
86. Ghrici, M., S. Kenai, and E. Meziane, *Mechanical and durability properties of cement mortar with Algerian natural pozzolana*. Journal of Materials Science, 2006. **41**(21): p. 6965-6972.
87. Talbot, C., et al., *Properties of mortar mixtures containing high amount of various supplementary cementitious materials.*, in *CANMET/ACI Fifth International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*. 1995: Milwaukee, USA. p. 125-152.
88. Andrade C, *Calculation of chloride diffusion coefficients in concrete from ionic migration measurements*. Cement and Concrete Research, 1993. **23**(3): p. 724-742.
89. Cochet G and Sorrentino F, *Limestone filled cements: Properties and uses*. Mineral admixtures in cement and concrete. 1993: ABI Book Private Limited.
90. Tosun, K., et al., *Effects of limestone replacement ratio on the sulfate resistance of Portland limestone cement mortars exposed to extraordinary high sulfate concentrations*. Construction and Building Materials, 2009. **23**(7): p. 2534-2544.
91. Sideris, K.K., A.E. Savva, and J. Papayianni, *Sulfate resistance and carbonation of plain and blended cements*. Cement and Concrete Composites, 2006. **28**(1): p. 47-56.
92. Kevser, D.G.A., *Sulfate Resistance of Blended Cements: With Fly Ash and Natural Pozzolan*. 2010: LAP LAMBERT Academic Publishing 112.
93. Irassar E.F, *Sulfate attack on cementitious materials containing limestone filler — A review*. Cement and Concrete Research, 2009. **39**(3): p. 241-254.
94. Lee, S.T., et al., *Effect of limestone filler on the deterioration of mortars and pastes exposed to sulfate solutions at ambient temperature*. Cement and Concrete Research, 2008. **38**(1): p. 68-76.
95. Hartshorn, S.A., J.H. Sharp, and R.N. Swamy, *The thaumasite form of sulfate attack in Portland-limestone cement mortars stored in magnesium sulfate solution*. Cement and Concrete Composites. **24**(3-4): p. 351-359.
96. Harald, J., *Thaumasite formed by sulfate attack on mortar with limestone filler*. Cement and Concrete Composites, 2003. **25**(8): p. 955-959.
97. Sawan, J.S., *Strength and Shrinkage of Natural Pozzolanic Mortar in Hot Weather. Journal of Materials in Civil Engineering*, 1992. **4**(2): p. 153-165.
98. Itim, A., K. Ezziane, and E.-H. Kadri, *Compressive strength and shrinkage of mortar containing various amounts of mineral additions*. Construction and Building Materials, 2011. **25**(8): p. 3603-3609.
99. Hassan, K.E., J.G. Cabrera, and R.S. Maliehe, *The effect of mineral admixtures on the properties of high-performance concrete*. Cement and Concrete Composites, 2000. **22**(4): p. 267-271.
100. Tsivilis, S., et al., *Properties and behavior of limestone cement concrete and mortar*. Cement and Concrete Research, 2000. **30**(10): p. 1679-1683.

101. Andrade, C., Alonso, M.C., Gonzalez, J.A.,, *An initial effort to use corrosion rate measurements for estimating rebar durability corrosion rates of steel in concrete,*, in *ASTM Special Technical Publication STP 1065,*, N.S.B.e. al., Editor. 1990, ASTM: Philadelphia.

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